CRITICAL REVIEWS IN
PLANT SCIENCES

Volume 30, Numbers 1–2, 2011

Special Issue: Towards a More Sustainable Agriculture
Guest Editors: Maurizio G. Paoletti, Tiziano Gomiero, and David Pimentel

CONTENTS

Critical Reviews in Plant Sciences, 30:1, 2011

ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.553147

Towards a More Sustainable Agriculture

Foreword

Critical Reviews in Plant Sciences is pleased to devote these issues to research in Sustainable Agriculture. The general topic of "sustainability" has been discussed in many regards—from housing to population growth, land usage to the effects of pollution on the environment, and so on. Intertwined among all the issues encompassed by sustainability is that of a sustainable food source, without which global society would certainly crumble. These very timely and thoughtful reports take a careful look at issues confronting conversion of our agricultural base into a truly sustainable model. In particular, organic approaches are mentioned and discussed. But also importantly, uses of the wild landscape as food sources are examined and education of the populace on the needs and methods of sustainability are discussed. Throughout the issue, the authors make a case for the need to achieve more sustainability of our food and fiber supply, as well as the consequences for not doing so.

We are especially indebted to Guest Editor Professor Tiziano Gomiero for taking the lead on this project, along with David Pimentel and Maurizio G. Paoletti for their contributions. It is important to note that Professors Pimentel and Paoletti are long-time members of the CRPS editorial board and the Guest Editors' collective talents can be seen throughout the issue.

This is the third in a series of special issues that are periodically published by CRPS. We hope that these articles will provide an enduring science-based backdrop for technical, social, and policy-making decisions required to deal with environmental challenges facing our changing world.

Dennis J. Gray
Robert N. Trigiano
Editors-in-Chief

Critical Reviews in Plant Sciences, 30:2–5, 2011

ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.553148

Introduction to the Special Issue: Towards A More Sustainable Agriculture

Maurizio G. Paoletti,[1] Tiziano Gomiero,[1] and David Pimentel[2]
[1]*Laboratory of Agroecology and Ethnobiology, Department of Biology, Padova University, Padova 35121, Italy*
[2]*College of Agriculture and Life Sciences, Cornell University, Ithaca, New York 14853, USA*

Agriculture provides food, fiber, construction materials, biomass, and “green energy.” It also contributes to an environmentally-friendly environment. Our societies are totally dependent upon agriculture and the photosynthetic pathway contributed by sunlight.

When humans began to rely on agriculture for their subsistence, civilizations flourished while humans spread all over the globe, transforming ecosystems to provide for their ever-increasing needs (Diamond, 1998; Bellwood, 2005; Montgomery, 2007a; Murphy, 2007; Ponting, 2007). According to Ruddiman (2005a, 2005b), early human activity, such as forest conversion to agricultural land, extensive use of fire, and wet rice cultivation, resulted in high Green House Gasses emission (GHGs), able to alter the earth climate long before industrial revolution took place.

Agricultural societies had to deal with the need to feed an growing population and to cope with the increasing complexities of their societies (Tainter, 1988; Johnson and Earle, 2000). As populations increased, pressure on the agricultural system led to reduced soil fertility and threatened its sustainability. Soil erosion led to soil exhaustion (loss of organic matter and its fertility) that impaired agro-ecosystem resilience, making it difficult to cope with the effects of climate extremes. Among the practices that led to the mismanagement of the soil were deforestation, fires, tillage, short rotation, irrigation (leading to the salinization of the soil), and a tendency to adopt monoculture rather than crop diversity (King, 1911; Carter and Dale, 1974; Tainter, 1988; Hillel, 1991; Diamond, 2005; Montgomery, 2007a; Ponting, 2007). Carter and Dale (1974) suggested that civilizations tend to collapsed in about 20 generations, apart from those relying, for soil fertilization, on river.

In the twentieth century, with the advent of fossil fuels, agriculture experienced an incredible boost. Thanks to chemical fertilizers and pesticides and the availability of other sources of energy, this helped to increase crop yields. In addition, the new high yielding varieties (HYVs) (or high-response varieties) developed in the 1960s by Norman Borlaug (1914–2009, Nobel Peace Price in 1970) and colleagues, helped to increase crop yields (Borlaug, 1970; Conway, 1998). With the “Green Revolution” the productivity of the main agriculture crops increased up to 4–5 times, helping to cope with the severe food scarcity and famine hitting many highly populated developing countries (Conway, 1998; Smil, 2000; Tilman *et al*., 2001; Pimentel and Pimentel, 2008). The main characteristics of the HYVs can be summarized as: having shorter stems than traditional cultivars, being genetically homogeneous and much more productive under high rates of fertilizers (e.g., synthetic nitrogen). However, HYVs were also weaker than their traditional relatives and more prone to pests and diseases (Conway, 1998).

In the last half century, the great abundance of cheap food (along with medical advances) led to increasing population growth, and contrary to the hopes of the green revolution, whose goal was to put an end to hunger, the FAO at present estimates that 1.02 billion people are hungry and undernourished worldwide in 2009. This represents more hungry people than at any time since 1970 (FAO, 2009; UNEP, 2009). When considering malnutrition in all its facets, it has been estimated that, at present, about 60% of the world population can be considered malnourished (Pimentel and Pimentel, 2008). It was Borlaug himself that warned, in his Nobel lecture, that unless the rate of human reproduction was curbed, the success of the Green Revolution would only be ephemeral (Borlaug, 1970). Some scholars argue, however, that remaining malnutrition is more a matter of access to food rather than one of insufficient availability and that there are additional social-political issues that play an important role in this problem (Sen, 1982; Conway, 1998; Smil, 2000; FAO, 2009).

Over the next decades the world’s population is expected to grow from 6.8 billion in 2008 (medium estimates) to 8.3 billion by the 2030, and to 9.2 billion by the 2050 (Cohen, 2003; UN, 2007; FAO, 2008; UNEP, 2009). Scenario analysis indicates a possible stop to population growth by the end of the century (Lutz *et al*., 2001, 2004). Other scholars, however,

---

Address correspondence to M. G. Paoletti, Laboratory of Agroecology and Ethnobiology, Department of Biology, Padova University, Padova, 35121, Italy. E-mail: paoletti@bio.unipd.it

remain skeptical (e.g., Hopfenberg and Pimentel, 2001) arguing that, contrary to the widely held belief that food production must be increased to feed the growing population, experimental and correlational data indicate that human population growth varies as a function of food availability, so that by increasing food production the effect will be an increase in the human population.

Recent studies suggest that the world will need 70 to 100% more food by 2050 (FAO, 2008; World Bank, 2008). So a new challenge lies ahead: to find a means to feed 9 billion with less land, water, and energy in the coming decades (Conway, 1998; Smil, 2000; Tilman *at al.*, 2002; Godfray *et al*., 2010).

Increasingly, intensive agricultural practices are affecting the very sustainability of our support system, the soil (Pimentel *et al*., 1995; Montgomery, 2007b). Croplands and pastures already occupy about 50% of the land surface (Foley *et al*., 2005), with large effects on biodiversity conservation (Paoletti *et al*., 1992; Krebs *et al*., 1999; Millennium Ecosystem Assessment, 2005). Agriculture accounts for 70% of water used by human activities (Molden, 2007). The use of agrochemicals is costly in terms of energy use (Pimentel and Pimentel, 2008), represents a threat to biodiversity and human life (Lipsitch *et al*., 2002; Lyons, 2009; Vitousek *et al*., 2009; Pimentel, 2010), and can cause a high level of water pollution (Molden, 2007; Moss, 2008). It is therefore urgent to find more ecological ways of limiting pests (Altieri and Nicholls, 2004; Gurr *et al*., 2004; Pimentel and Cilveti, 2007). At the same time, agricultural practices should reduce both their environmental impact and their use of non-renewable resources (e.g., fossil fuel energy) (Millennium Ecosystem Assessment, 2005; Pimentel and Pimentel, 2008).

Vast industrialized agriculture also contributes greatly to impoverished crop biodiversity, with the loss of a large number of agricultural species and varieties (Fowler and Hodgkin, 2005). A cultural aspect that may be worth mentioning, is that when Western agriculture package is transferred to other continents, it tends to dismiss, or overlook, many sorts of traditional local resources—such as insects and other arthropods, earthworms, small vertebrates and wild plants (insects and earthworms, for instance, may total more than 3,000 kg/ha; Pimentel and Pimentel, 2008). These local resources can play an important role in guaranteeing food security in poor rural areas, but are often neglected because of the Western perception that these are not "proper food" for people (Paoletti and Bukkens, 1997; Paoletti, 2005; Ochatt and Jain, 2007).

We are aware that a topic such as agriculture sustainability is broad and highly complex (Smil, 2000; Giampietro, 2004; Francis *et al.*, 2006; Bohlen and House, 2009; UNEP, 2009; NRC, 2010). It includes aspects ranging from ecology to genetics, from agronomy to soil management, from economics to politics. The point we wish to make with this special issue is to offer some additional ideas and comments on some issues in the field of sustainable agriculture.

The first two papers address directly the sustainability issue.

The first paper, "Is there a need for a more sustainable agriculture?" (Gomiero and colleagues), reviews a number of problems concerning the impact of conventional agriculture on the environment and soil, and discusses some theoretical approaches and techniques that may offer useful strategies for a more sustainable agriculture. The second paper, "Agriculture and social complexity in ancient societies: Causes, consequences, and implications for sustainability" (Tainter), addresses the relations between agriculture, society complexification and the pattern of collapse associated with complex societies. Tainter defines sustainability as a matter of problem solving and a process of continuous adaptation. He points out that, paradoxically, as problems arise, addressing these problems requires "complexification" of the society and in turn more resources consumption. Some ideas concerning the possibility to deal with the sustainability issue are presented.

The second pair of papers deals with the use of energy in agriculture, and the sector's dependence on fossil fuels. The paper by Pimentel, "Food for thought: A review of the role of energy in current and evolving agriculture," analyzes the energetic costs of food production, while the paper by Arizpe-Ramos and colleagues, "Food security and fossil energy dependence: An international comparison of the use of fossil energy in agriculture (1991–2003)," reviews global trends in energy consumption in agriculture.

A third group of papers deals with management issues and focuses on possible practices for achieving more sustainable agriculture.

The paper by Francis and Porter, "Ecology in sustainable agriculture practices and systems," reviews a number of practices that can be employed to improve agricultural efficiency and sustainability.

Pest control is a key issue in agriculture management, and pesticide use a major environmental impact. Eckstrom and Ekbom, "Pest control in agroecosystems: An ecological approach," review the recent achievements in the field of natural pest control and how this can contribute to reducing the environmental impact of agriculture.

During recent decades organic farming has achieved wide attention both from consumers and policy makers because of its call for promoting an agriculture free from agrochemicals and based on ecological practices, and for its concern for the preservation of biodiversity. The paper by Gomiero and colleagues, "Environmental impact of different agricultural management practices: Conventional vs. organic agriculture," summarizes this story and the foundation of the organic movements and reviews research works assessing the achievement of organic farming vs. conventional farming for a number of environmental issues.

Over time, the number of crops and local varieties have drastically reduced in most regions, with the result that fewer plants and animals now compose the actual base of our food. The paper "A heuristic framework for identifying multiple ways of supporting the conservation and use of traditional crop varieties within the agricultural production system" by Jarvis and colleagues, addresses this problem and discusses the different ways of supporting farmers and farming communities in the maintenance of traditional varieties and crop genetic diversity within their production systems.

A fourth selection of papers deals with food quality and the knowledge about the use of semi-domesticated and wild plants. Whether organically grown crops have more nutritional propertied then conventional crops is matter of debate. The paper by Brandt and colleagues, "Agroecosystem management and nutritional quality of plant foods: The case of organic fruits and vegetables," reviews the present knowledge about the nutritional characteristics of organic products. Turner and colleagues in "Edible wild and tended plants, traditional ecological knowledge and agroecology," explore local knowledge of semi-domesticated or tended and wild plants and their nutritional as well as their possible economic role .

The closure of the special issue is provided by Francis and colleagues with a paper titled "Innovative education in agroecology: Experiential learning for a sustainable agriculture," which reviews recent experiences in the field of agriculture education. It is vital that we develop sound agricultural practices, if we want to have a new generation of scientists able to deal with the complex field of sustainable agriculture.

We wish to thank all the authors who participated in this project, as well as the editors of CRPS for their interest and sensitivity on this vital issue.

REFERENCES

Altieri, M., and Nicholls, C. I. 2004. *Biodiversity and Pest Management in Agroecosystems.* (2nd ed.) CRC Press, Boca Raton, FL.

Bellwood, P. 2005. *First Farmers: The Origin of Agricultural Societies*. Blackwell, MA.

Bohlen, P. J., and House, G. (Eds.) 2009. *Sustainable Agroecosystem Management*. CRC Press, Boca Raton, FL.

Borlaug, N. 1970. The Green Revolution, Peace, and Humanity—Nobel Lecture. http://nobelprize.org/nobel_prizes/peace/laureates/1970/borlaug-lecture.html Accessed on 23 November 2009.

Carter, V. G. and Dale, T. 1974. *Topsoil and Civilization*. University of Oklahoma Press, Norman, OK.

Cohen, J. E. 2003. Human population: The next half century. *Science* **302:** 1172–1175.

Conway, G. 1997. *The Doubly Green Revolution: Food for All in the Twenty-First Century*. Penguin, London.

Diamond, J. 1998. *Guns, Germs and Steel: A Short History of Everybody for the Last 13,000 Years.* Vintage, London.

Diamond, J. 2005. *Collapse: How Societies Choose to Fail or Succeed*. Penguin, London.

FAO. 2009. *The State of Food Insecurity in the World*. FAO, Rome. http://www.fao.org/docrep/012/i0876e/i0876e00.HTM Accessed on January 20, 2010.

Ferry, N., and Gatehouse, A. M. R. (Eds). 2009. *Environmental Impact of Genetically Modified Crops*. CABI, Wallingford, UK.

Foley, J. A., DeFries, R., Asner, G. P., Barford. C., and fifteen other. 2005. Global consequences of land use. *Science* **309:** 570–574.

Fowler, C., and Hodgkin, T. 2005. Plant genetic resources for food and agriculture: Assessing global availability. *Annu. Rev. Env. Resour.* **29:** 143–179.

Francis, C. A., Poincelot, R. P., and Bird, G. W. (Eds). 2006. *Developing and Extending Sustainable Agriculture. A New Social Contract*. Haworth Flood & Agricultural Products Press, New York.

Giampietro, M. 2004. *Multi-scale Integrated Analysis of Agroecosystems*. CRC Press, Boca Raton, London.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., and Toulmin, C. 2010. Food security: The challenge of feeding 9 billion people. *Science* **237:** 812–818.

Gurr, G. M., Wratten, S. D., and Altieri, M. A. (Eds) 2004. *Ecological Engineering for Pest Management: Habitat Manipulation for Arthropods*. CSIRO Publishing, Collingwood, Australia.

Hillel, D. 1991. *Out of the Earth. Civilization and the Life of the Soil.* California Univ. Press, Berkeley, CA.

Hopfenberg, R., and Pimentel, D. 2001. Human population numbers as a function of food supply. *Environment, Development and Sustainability* **3:** 1–15.

Johnson, A.W., and Earle, T., 2000. *The Evolution of Human Societies. From Foraging Group to Agrarian State*. Stanford University Press, Stanford, CA.

King, F. H. 1911. *Farmers of Forty Centuries: Or Permanent Agriculture in China, Korea and Japan*. Mrs. King, Madison. The book is available at URL http://www.gutenberg.org/etext/5350 (and reprinted in 1990 by Rosale Press)

Krebs, J. R., Wilson, J. D., Bradbury, R. B., and Siriwardena, G. M. 1999. The second Silent Spring? *Nature* **400:** 611–612.

Lipsitch, M., Singer, R.S ., and Levin, B. R. 2002. Antibiotics in agriculture: When is it time to close the barn door? *PNAS* **99:** 5752–5754.

Lutz, W., Sanderson, W., and Scherbov, S. 2001.The end of world population growth. *Nature* **412:** 543–545.

Lutz, W., Sanderson, W., and Scherbov, S. (Eds) 2004. *The End of World Population Growth in the 21th Century*. Earthscan, London.

Lyons, G., 2009. Effects of pollutants on the reproductive health of male vertebrate wildlife - Males under threat. CHEM Trust (Chemicals, Health and Environment Monitoring) http://www.chemtrust.org.uk/documents/Male%20Wildlife%20Under%20Threat%202008%20full%20report.pdf Accessed on 10 May 2010.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington, DC. http://www.millenniumassessment.org/en/Synthesis.aspx Accessed 25 November 2009.

Molden, D. (Ed.). 2007. *Water for Food, Water for Life. A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London. The publication is available on internet at URL: http://www.iwmi.cgiar.org/assessment/Publications/books.htm

Montgomery, D. R. 2007a. *Dirt: The Erosion of Civilization*. University of California Press, Berkeley.

Montgomery, D. R. 2007b. Soil erosion and agricultural sustainability. *PNAS* **104**:13268–13272.

Moss, B. 2008. Water pollution by agriculture. *Phil. Trans. R. Soc. B* **363:** 659–666.

Murphy, J. D. 2007. *People, Plant & Genes*. Oxford Univ. Press, New York.

NRC (National Research Council). 2010. *Toward Sustainable Agricultural Systems in the 21st Century.* National Academies Press http://www.nap.edu/catalog/12832.html Accessed on 20 March 2010.

Ochatt, S., and Jain, S. M. 2007. *Breeding of Neglected and Under-Utilized Crops Spices and Herbs*. Science Publishers, Enfield, New Hampshire.

Paoletti M.G. (Ed.) 2005. *Ecological Implications of Minilivestock. Insects, Rodents, Frogs and Snails*. Science Publishers, Enfield, New Hampshire.

Paoletti, M. G., and Bukkens, S.G.F. 1997. Minilivestock. *Ecology of Food and Nutrition*. **36:** Special Issue.

Paoletti, M. G., Pimentel, D., Stinner, B. R., and Stinner, D. 1992. Agroecosystem biodiversity: Matching production and conservation biology. *Agric. Ecosys. & Environ.* **40:** 3–26.

Pimentel, D. 2010. *The Effects of the Resistance of Antibiotics and Pesticides on U.S. Public Health*. Institute of Medicine, National Academy of Sciences, Washington, D.C. (In Press)

Pimentel, D., and Cilveti, M. V. 2007. Reducing pesticide use: successes. **In:** *Encyclopedia of Pest Management*, Volume **2:** 551–552. CRC Press, Taylor and Francis Group, Boca Raton, FL.

Pimentel, D., and Pimentel, M. 2008. *Food, Energy, and Society.* 3rd ed. CRC Press, Boca Raton, FL.

Ponting, C. 2007. *A New Green History of the World: The Environment and the Collapse of Great Civilizations*. Vintage Books, London.

Ruddiman, W. 2005a. *Plows, Plagues, and Petroleum*. Princeton University Press, Princeton, NJ.

Ruddiman, W. 2005b. How did humans first alter global climate? *Scientific American* **March:** 46–53.

Sen, A. 1982. *Poverty and Famines: An Essay on Entitlements and Deprivation.* Oxford, Clarendon Press.

Smil, V. 2000. *Feeding the World: A Challenge for the Twenty-First Century*. The MIT Press, Cambridge, MC.

Tainter, J. A. 1988. *The Collapse of Complex Societies*. Cambridge University Press, Cambridge.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. 2002. Agricultural sustainability and intensive production practices. *Nature* **418:** 671–677.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D. and Swackhamer, D. 2001. Forecasting agriculturally driven global environmental change. *Science* **292:** 281–284.

UN (United Nations). 2007. Population Newsletter. Number 83. http://www.un.org/esa/population/publications/popnews/Newsltr_83.pdf Accessed on 2 July 2009.

UNEP (United Nations Environmental Programme). 2009. The environmental food crisis the environment's role in averting future food crises a UNEP rapid response assessment. UNEP, GRID-Arendal, http://www.grida.no/publications/rr/food-crisis/ Accessed on 12 May 2010.

Vitousek, P. M., Naylor, R., and 15 others. 2009. Nutrient imbalances in agricultural development. *Science* **324:** 1519–1520.

World Bank. 2008. *World Development Report 2008: Agriculture for Development*. World Bank, Washington, DC. http://siteresources.worldbank.org/INTWDR2008/Resources/WDR_00_book.pdf Accessed 27 October 2009.

Critical Reviews in Plant Sciences, 30:6–23, 2011

ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.553515

Is There a Need for a More Sustainable Agriculture?

Tiziano Gomiero,[1] David Pimentel,[2] and Maurizio G. Paoletti[1]
[1]*Laboratory of Agroecology and Ethnobiology, Department of Biology, Padova University, Padova 35121, Italy*
[2]*College of Agriculture and Life Sciences, Cornell University, Ithaca, New York 14853, USA*

Table of Contents

In this paper the environmental impact of current agriculture practices is reviewed. Soil loss (along with soil fertility), increasing water demand from agricultural practices and environmental pollution caused by the intensive use of agrochemicals, are among the most pressing issues concerning agriculture sustainability. Biodiversity loss due to land use change and emission of greenhouse gasses from agricultural activities are also causes for concern. A

Address correspondence to T. Gomiero, Laboratory of Agroecology and Ethnobiology, Department of Biology, Padova University, Padova 35121, Italy. E-mail: tiziano.gomiero@libero.it

Referee: Prof. Deborah Stinner, Dept. of Entomology, Ohio Agriculture Research and Development Center, The Ohio State University.

number of alternative agricultural practices are also presented that can help to make agriculture less environmentally damaging by reducing the use of natural resources, limiting inputs and preserving soil fertility and biodiversity. We think that there is room for a different and more ecological agriculture and that research should be implemented in order to better assess the potential and constraints of the different options. However, notwithstanding the great achievements of the "Green Revolution," the world will need 70 to 100% more food by 2050. So a new challenge lies ahead: how to feed nine billion with less land, water and energy, while at the same time preserving natural resources and soil fertility? Technical advances are important in order to meet the future needs, but addressing key socioeconomic issues, such as the inequality in the access to resources, population growth, and access to education are also a priority if we want to properly deal with sustainability. It may require our society to change some of its paradigms and "values" if we wish to preserve our support system, the soil and its health, for the future generations.

Keywords sustainable agriculture, agroecology, food security, environmental impact, natural resources, multifunctionality, multi-criteria

I. AGRICULTURE: PRODUCTIVITY VS. SUSTAINABILITY

In the twentieth century agricultural productivity experienced an incredible leap forward: fossil fuels became available as a cheap and (deemed) unlimited energy source, allowing the industrial production of chemical fertilizers and pesticides, and the mechanization of agriculture (Smil, 2000; 2004). In the 1970s, Norman Borlaug (1914–2009, Nobel Peace Prize in 1970) and colleagues developed new high-yielding wheat varieties (HYVs, termed also high-response varieties), which could benefit from the availability of these new fertilizers, and boost productivity. HYV grains had shorter stems than traditional cultivars, were genetically homogeneous, and were more productive but needed a higher rate of fertilizer intake (e.g., nitrogen). However, they resulted in crops more prone to pests and diseases. Even if some varieties have certain kinds of disease resistance built in, newly developed synthetic pesticides were necessary to keep pests out of the crops.

With the "green revolution" (as this period is referred to), the productivity of the main agriculture crops, on average, more than doubled and some cereals reached a staggering 4 to 5 times (Smil, 1991; 2000; Tilman *et al.*, 2002; Pimentel and Pimentel, 2008), helping to meet world food demand and saving hundreds of millions from starvation. Asia, for example, which was threatened by hunger and mass starvation as late as the mid-1960s, became self-sufficient in staple foods within 20 years even though its population more than doubled (Hazell and Wood, 2008).

However, along with the increase in food production, population levels kept increasing (Cohen, 2003), and paradoxically this huge boost eventually has not solved the problem of the hungry world. Late official statistics (WFP, 2008; Fao, 2010) estimates that in the last years form about 920 to 1,020 million people were undernourished and chronically hungry (based only on calorie and protein malnutrition). The real figure, however, is much larger. When other forms of nutritional deficiency are included (e.g., those caused by lack of vitamins and minerals), 3.7 billion people can be considered malnourished (FAO, 2008; UNEP, 2009).

Recent studies suggest that the world will need 70 to 100% more food by 2050 (World Bank, 2008). So a new challenge lies ahead: how to feed 9 billion with less land, water, and energy (Borlaug, 2007; Godfray *et al.*, 2010)? The quest for higher food production is more active than ever, to the point that a new "Green Revolution" is persistently called for (e.g., Conway, 1997; Borlaug, 2007; Hahlbrock, 2007; Phelan, 2009; Godfray *et al.*, 2010).

At present, however, malnutrition is more a matter of access to food rather than one of insufficient availability (Sen, 1982; Conway, 1997; Smil, 2000; Stone, 2002; Patel, 2008). Hunger is more a problem of income distribution rather than of food shortage. Stone (2002, p. 615) states that "*The fact that so many go hungry while the granaries are bursting is widely recognized in India.*" But even in countries of food plenty, such as the United States and those in Europe, a larger and larger fraction of poor people suffer from malnutrition due to food shortage. A survey of the U.S. Department of Agriculture states that in 2008, 49 million people went without access to sufficient food in the United States, and more than one in five children went without enough food during the same year (Nord *et al.*, 2009). This cannot be attributable to lack of food supply due to low crop yields in the United States, especially when by 2012, 30% of American corn production is expected to be devoted to generating ethanol, accounting for 7.4 % of projected American total gasoline consumption (USGOA, 2007; Koplow and Steenblik, 2008).

This famine tragedy in many developing countries clashes with the obesity epidemic in the industrialised countries, and among the newly rich people in developing countries. According to the WHO's latest projections globally in 2005 approximately 1.6 billion adults (ages 15+) were overweight, and at least 400 million adults were obese (WHO, 2005). WHO further projects that by 2015, approximately 2.3 billion adults will be overweight and more than 700 million will be obese. Obesity is related to a number of diseases such as different types of cancer, kidney problems, and many adverse metabolic effects on blood pressure, cholesterol, triglycerides, and insulin resistance among others. This new epidemic is also very costly for the society, so that consumption of sugary and fatty foods should be a matter of concern for national health policy (Nestle, 2003).

A vegetarian diet of an equivalent 2,200 kcal per day requires 33% less fossil energy than the average American diet with meat (Pimentel and Pimentel, 2008). The Food and Drug Administration (FDA, 2007) recommends an average daily consumption of 2,000 kcal for females and 2,500 kcal per day for males, much less than the average American is consuming today. Reducing the caloric intake would significantly reduce the total energy expended for food production as well as help lessen the obesity problem.

When coming to the food system, it is disturbing that 30–40% of the food produced in the field is wasted through the food system; in industrialized countries it is estimated that 15–20% just passes directly from our refrigerators to the bin (Smil, 2000; Stuart, 2009; Godfray *et al*., 2010). Food wastage clashes with the increasing costs of intensive agricultural practices. Costs are being paid in terms of loss of soil and fertility, reduction of water supply, threat to biodiversity, and pollution from agrochemicals (Tilman *et al*., 2001; 2002; Jackson *et al*., 2005; Millennium Ecosystem Assessment, 2005; Molden, 2007; Vitousek *et al*., 2009).

All this calls for a time of careful re-evaluation: should we try to understand how our food system became this perverse? Why are we pushing for intensive agriculture to produce more crops, when we throw a lot away? Why has this increased production and consumption made us sick and unhealthy? Why do we accept a food system that impoverishes the soil, threatens biodiversity, and contaminates our environment?

II. ENVIRONMENTAL COSTS

The huge agriculture productivity boost achieved with the introduction of modern agriculture did not come without a cost. The environmental impact of agricultural activity increased too, and the overall efficiency (as output/input) declined sharply (Tilman *et al*., 2001; 2002; Millennium Ecosystem Assessment, 2005; Hazell and Wood, 2008; Pimentel and Pimentel, 2008).

A. Human Appropriation of Net Primary Productivity

Croplands and pastures have become one of the largest terrestrial biomes on the planet, rivaling forest cover in extent and occupying about 50% of the land surface (Foley *et al*., 2005). The coming 50 years are likely to be a period of rapidly expanding, global human environmental impacts. Future agricultural practices will shape, perhaps irreversibly, the surface of the Earth, including its species, biogeochemistry, and utility to society (Tilman *et al*., 2001; Foley *et al*., 2005).

Vitousek *et al*. (1986) proposed to use the Human Appropriation of Net Primary Productivity (HANPP) as an indicator of human pressure on the environment. Vitousek *et al*. (1986; 1997) estimated that until 1700, millions of humans used less than 5% of nature's Net Primary Productivity (NPP) while in the second half of the 1900s, the HANPP already reached 40%. In 2000, it has been estimated that HANNP reached 50% (Haberl *et al*., 2002; Imhoff *et al*., 2004). However, other authors suggest a wider range. Rojstaczer *et al.* (2001) estimate that humans appropriate 10 to 55% of terrestrial photosynthesis products, the broad range reflecting uncertainty in key parameters and making it difficult to ascertain whether we are approaching crisis levels in our use of the planet's resources.

Also, other indicators of sustainability (or better of *unsustainability*) such as the Ecological Footprint (Wackernagel and Rees, 1996) are telling us that the ecological overshoot has already reached an alarming stage. Today, humanity uses the equivalent of 1.3 planets to provide the resources we use and absorb our waste (Global Footprint Network, 2009), which dramatically indicates that humans are already living far beyond sustainability (Wackernagel *et al*., 2002). [The Ecological Footprint measuring system has been criticized by some scholars (e.g., van den Bergh and Verbruggen, 1999; Fiala, 2008a) on the basis that it underestimates the real impact of agricultural activities on long-term resource sustainability, and presents a logical flaw in the comparison of consumption levels and earth biocapacity].

With a human population that will grow from 6.8 billion in 2007 (PRB, 2009) to a staggering figure of 8.3 billion by the 2030 (FAO, 2002) and 9.2 billion in 2050 (UN, 2007a; Godfray *et al*., 2010), we have to expect HANPP to further increase just to keep pace with the production of food and fiber. In addition, more land will be lost to urbanization, leading to the destruction of vast areas along with its ecosystems.

B. Soil

Agricultural intensification leads to increasing water use and loss of soil fertility, threatening long-term crop productivity by increasing soil degradation and causing water shortages.

About 40% of global croplands may be experiencing some degree of soil erosion, reduced fertility, or overgrazing (Pimentel *et al*., 1995; Wood *et al*., 2000; Montgomery, 2007; Reynolds *et al*., 2007). Soil erosion has been estimated to reduce yields on about 16% of agricultural land, especially cropland in Africa and Central America and pastures in Africa (Wood *et al*., 2000). Dry land prone to degradation covers about 40% of the earth's land surface and is tied with the subsistence of 2.5billion people. In such areas agricultural management plays a key role in guaranteeing fertility conservation (Reynolds *et al*., 2007).

At present, the accelerated rates of erosion experienced are causing major modifications to carbon, nitrogen, and phosphorus biogeochemical cycles (Vitousek *et al*., 2009; Quinton *et al*., 2010). Resistance of soils to erosion is closely linked to the stabilizing influence of organic matter and vegetation cover. In regions such as Asia and Africa, where soil erosion is associated with reduced vegetation cover, the loss of soil carbon can trigger catastrophic shifts to severely degraded landscapes (Berhe *et al*., 2007; Quinton *et al*., 2010).

Most of the Soil Organic Matter (SOM) is found in the topsoil (15–25 cm of the A horizon) in the form of decaying leaves and stem material. SOM is of key importance for soil fertility (Allison, 1973; Altieri, 1987; Pimentel *et al*., 1995; Pimentel and Kounang, 1998; Lal, 2004; Bot, 2005).

The Soil Organic Carbon (SOC) pool to 1 m depth ranges from 30 tons ha^{-1} in arid climates, to 800 tons ha^{-1} in organic soils in cold regions, and a predominant range of 50 to 150 tons ha^{-1} (Lal, 2004). Fertile agricultural soils can contain up to 100 tons of organic matter per hectare (or 4% of the total soil weight), and in the case of most agricultural soils, SOM represents 1–5% of topsoil (Russell, 1977). Conventional agricultural practices that tend to leave soil uncovered for long periods of the year are responsible for topsoil erosion and reduction of its SOM content. Soil removed by either wind or water erosion is 1.3–5.0 times richer in organic matter than the soil left behind (Barrows and Kilmer 1963; Allison 1973; Lal, 2004; 2010). About 95% of soil nitrogen and 25–50% of soil phosphorus are contained in the SOM-containing topsoil layer (Allison, 1973; Lal, 2010), the importance of which is such that in one study it was estimated that the reduction of SOM from 1.4% to 0.9% lowered the grain yield potential by 50% (Libert, 1995).

When poorly practiced, intensive agriculture poses a threat to soil ecology in two ways: it accelerates SOM matter oxidation and depletion, and predisposes soil to increased erosion, leading to mandatory application of nitrogen fertilizers (Allison, 1973; Pimentel *et al.*, 1995; Matson *et al.*, 1997; Rasmussen *et al.*, 1998; Lal, 2004; Montogmey, 2007; NRC, 2010). Agricultural practices such as no-till agriculture, or minimum tillage, can help to reduce soil loss and restore soil fertility (Lal, 2004; 2007; 2010; NRC, 2010).

C. Water Resources

Currently, on a global scale, 70% of the 3,800 km^{3}of water that humans use is directed towards agriculture, 20% towards industry and 10% towards urbanized areas (Molden, 2007). By 2050 agricultural water use is expected to increase by 13% (Molden, 2007).

The production of common crops in many parts of the world requires a great amount of water, from a few hundreds to a few thousands times the final crop mass (Pimentel *et al.*, 2004; Smil, 2002; Molden, 2007; Rockstrom *et al.*, 2007). Estimated average values range from 0,65 m^3 kg^{-1} for corn, 1 m^3 kg^{-1} for wheat, 2 m^3 kg^{-1} for soybeans, up to 6 m^3 kg^{-1} for pork and 43 m^3 kg^{-1} for beef (Pimentel *et al.*, 2004; Pimentel and Pimentel, 2008). However, current levels of water productivity show large variations by commodity: 6.6–0.6 m^3 kg^{-1} for rice, 5–1 m^3 kg^{-1} for wheat, 3.3–0.5 m^3 kg^{-1} for corn, 0.33–0.15 m^3 kg^{-1}for potatoes, 33–10 m^3 kg^{-1} for beef (e.g., Molden, 2007, tab 7.3) The concepts of "virtual water" (Allan, 1998; FAO, 2002; Smil, 2008) and "water footprint" (Khan and Hanjra, 2009; Hoekstra *et al.*, 2009) have been proposed to assess the real cost of agricultural commodities in terms of water use.

Intensive irrigated agriculture can lead to waterlogging and salinization. Some irrigated lands have become heavily salinized, causing the worldwide loss of about 1.5 million hectares of arable land per year, along with an estimated $11 billion in lost production (Postel, 1999; Wood *et al*., 2000), as well as the depletion and chemical contamination of surface and groundwater supplies (Wood *et al*., 2000; Pimentel *et al.*, 2004; Moss, 2008). Approximately 40% of U.S. fresh water is deemed unfit for drinking or recreational use because of contamination by dangerous microorganisms, pesticides, and fertilizers (Pimentel *et al.*, 2004).

Agricultural impacts on freshwater and marine systems might include: effects on water composition (nutrient loss, with consequent eutrophication and food web modification), biocide leaching, suspended loads from soil erosion, hydrological cycle alteration (changed evapotranspiration rates and hence run-off and modification of river courses and irrigation water losses), effects of exotic species used, particularly in fish and crustacean culture, and physical habitat modification (channelization, channel modification, embankment and drainage) (Moss, 2008).

According to recent analysis, experts report that agricultural expansion and intensification have altered the quantity and quality of global water ways, and that these changes have increased the risk of catastrophic ecosystem regime shifts (Gordon *et al*., 2007). For example, during the twentieth century, humans increased the diversion of river water six-fold (Pretty *et al*., 2006; Molden *et al*., 2007).

As water becomes increasingly scarce in certain regions of the world, it will be important to increase water efficiency in irrigation and rain-fed agriculture. It is estimated that 2.8 billion people currently live in areas facing water scarcity, with agricultural water use expected to increase by 70–90% by 2050, because of changes in evapotranspiration (Molden *et al*., 2007). Increasing water use efficiency is then needed as well as increasing concern about the pattern of our food consumption. In this regard, above-mentioned indicators such as "virtual water" and "water footprint" will help assess the effect of human consumption patterns on water use (Molden *et al*., 2007; Hoekstra *et al*., 2009).

D. Agrochemicals

The Haber-Bosh industrial synthesis of ammonia in 1913 (Smil, 2004), and the discovery in 1939 of the insecticidal qualities of DichloroDiphenylTrichloroethane (DDT) by Swiss chemist Paul Hermann Müller (Müller, 1948), have revolutionized agriculture, and led to the production of cheap synthetic fertilizers and pesticides. The use of agrochemicals spread in the United States and Europe after World War II, following an exponential trend (Smil, 2004; Pretty, 2005; Vitousek *et al*., 2009).

Synthetic fertilizers have been at the core of the green revolution, but there is awareness that their widespread use can represent a serious threat for the environment (Smil, 2002; 2004; Tilman *et al*., 2002; Dalton and Brand-Hardy, 2003; Beman *et al*., 2005; Eickhout *et al*., 2006; Erisman *et al*., 2008; Vitousek *et al*., 2009). Pre-agricultural terrestrial Nitrogen (N) fixation has been estimated to have been 150–190 Mt N per year, while, at present, the aggregate anthropogenic fixation of N amounts to 160–170 Mt N per year (Cleveland *et al*., 1999; Smil, 2004).

Between 1960 and 1995, at a global scale, N fertilizer use on cereals increased sevenfold, whilst cereal yields more than doubled; however, N fertilizer efficiency (cereal yields divided by N fertilizer inputs) declined from over 70 to around 25 kg grain per kg N (Tilman *et al*., 2001; Cassman *et al*., 2002). The overall global nitrogen use efficiency of cereals decreased from $\sim$80% in 1960 to $\sim$30% in 2000 (Tilman *et al*., 2001; Erisman *et al*., 2008)

Global data for maize, rice, and wheat indicate that only 18% to 49% of nitrogen applied as fertilizer is taken up by crops; the remainder is lost to runoff, leaching, or volatilization (Cassman *et al*., 2002). In this case, in order to improve efficiency (both on energetic and economical bases, because producing synthetic N requires energy and costs money), and greatly benefit the environment, a more rational use of fertilizers would suffice. Actually, some authors demonstrated how N application can be reduced up to 50% without compromising yield or grain quality (Madson *et al*., 1998; Ju *et al*., 2009; Vitousek *et al*., 2009; Ahrens *et al*., 2010), in turn reducing N losses into the environment.

It has been estimated that in 2005 approximately 100 Mt N from the Haber-Bosch process was used in global agriculture: only 17 Mt N was consumed by humans in crop, dairy and meat products, the remainder ending up dispersed in the environment (Erisman *et al*., 2008)

Eickhout *et al.* (2006) estimated that NH_3, N_2O and NO emissions and nitrate leaching to groundwater will grow strongly towards 2030 because of the intensification of animal and crop production systems in developing countries. In the light of the above statements, a more careful and rational use N would be a win-win solution, being of agronomical, economical, and environmental benefit (Erisman *et al*., 2008; Vitousek *et al*., 2009).

Widespread use of pesticides on crops has lead to the emergence of many pesticide-resistant pests and pathogens (Hoy, 1998; Pimentel, 1997; Krebs *et al*., 1999; Johansen, 2003; Pretty, 2005). Concerning pest resistance, some authors argue for the need to embrace a “mitigation” strategy, contrary to the belief that we can manage it, such as Integrated Pest Management (IPM). However, in order for mitigation measures to be effective, a holistic approach to pest management is needed, requiring the management of the global environment. As Holy (1998, p. 1799) points out: “An effective paradigm for resistance mitigation has not yet been widely deployed. This is because we have failed to accept that satisfactory resistance mitigation is based on the development of effective, fully integrated multi-tactic IPM programmes. Such programmes ideally will consider the entire agroecosystem and acknowledge the role of monitoring, economic injury levels, biological controls, genetic controls, cultural controls, and biorational controls such as mating disruption, insect growth regulators and mass trapping. A key issue in such programmes should always be whether pesticides can be used in a precise and selective manner without disrupting natural enemies. Disruption of natural enemies is not limited to acute toxicity, but can occur if pesticides arc applied over a sufficiently large area so that natural enemies are limited in abundance by available food resources. It is time we recognize, as Stern *et al*. (1959) did, that true resistance mitigation requires a holistic approach to pest management.”

Moreover, pesticides also have a major impact on animal and human health. The book *Silent Spring* by Rachel Carson has been a landmark on this issue, raising public awareness of the side effects of chemicals that seemed to be a silver bullet to defeat pests. People can be exposed to excessive pesticide levels while working; via food, soil, water or air; or by directly ingesting pesticide products. Pesticides are known to cause 26 million human poisonings per year and 220,000 deaths (Richter, 2000). Along with other synthetic chemicals, some pesticides have a direct effect on the reproductive system of many high organisms, acting as endocrine disruptors, and inducing severe reproductive problems and modifying sexual behavior (Colborn *et al*., 1997; Lyons, 2009). Lu *et al*. (2006) demonstrate that an organic diet provides a dramatic and immediate protective effect against exposures to organophosphorus pesticides that are commonly used in agricultural production, in children who were most likely exposed to these compounds exclusively through their diet.

Dietary accumulation through the tropic chain, or biomagnification, can cause additional bioaccumulation, resulting in a thousand-fold increase in toxic substance chemical concentration s, and in increasing trophic levels in food webs, even at very low concentrations of the toxic chemicals in the environment (Kelly *et al*., 2007).

In the last decades efforts have been produced to reduce the use of pesticides (Pretty, 2005; Pimentel and Cilveti, 2007; Ekström and Ekbom, this issue).

In both Sweden and Indonesia, for instance, there have been notable reductions in pesticide use. Sweden has reduced pesticide use by 68% and Indonesia by 65% (*Pesticides News*, 435, 2001; Pimentel and Cilveti, 2007). Integrated Pest Management (IPM), a technique that combines biological control, improving host plant resistance and adopting appropriate farming practices to minimizing the use of pesticides, is regarded as the best option for the future (Ekström and Ekbom, this issue).

E. Biodiversity

Agricultural expansion has a direct impact on local biodiversity through landscape modification which in turn results in displacement of local populations and loss of ecosystem services.

The loss of native habitats and agricultural intensification, which displaces traditional varieties of seeds with modern high-yielding, but genetically uniform crops, are threatening biodiversity (both wild and domesticated) all over the globe (Wilson, 1988; Paoletti and Pimentel, 1992; Paoletti *et al*., 1992; Matson *et al*., 1997; Pimentel *et al*., 1997; Krebs *et al*., 1999; Wood *et al*., 2000; Donald *et al*., 2001; Tilmann *et al*., 2001, 2002; Green *et al*., 2004; Foley *et al*., 2005; Jackson *et al*., 2005; Millennium Ecosystem Assessment, 2005a; Chivian and Bernstein, 2008; Sachs *et al*., 2009). Farming, including land conversion to farmland, for instance, accounts for 37% of threats to bird species listed as threatened species (Green *et al*., 2005). Extensive industrialized agriculture also greatly contributes to impoverishing crop biodiversity, with the loss of a large number of agricultural species and varieties (Jackson *et al*., 2005; Fowler and Hodgkin, 2005).

This agricultural expansion threatens the benefit that biodiversity provides to crops by, for instance, pest control and other environmental services (Paoletti *et al*., 1992; Sommaggio *et al*., 1995; Altieri and Nicholls, 2004; Hillel and Rosenzweig, 2005; Bianchi *et al*., 2006; Sachs *et al*., 2009; Crowder *et al*., 2010). Furthermore, land use change has also a direct impact on rising CO_2 on global river run-off (Piao *et al*., 2007).

Aboveground and belowground components of ecosystems have traditionally been considered in isolation from one another, but it is now clear that there is strong interplay between them (Wardle *et al*., 2004). Many beneficial insects and parasitoids, for instance, spend most of their lifecycle underground before being active aboveground on the crops; preserving soil quality is, then, of foremost importance, so as to take advantage of those beneficial organisms for control of crop pests (Paoletti and Bressan, 1996). Stable litter on topsoil can encourage pests such as slugs, but can also feed detritivores and polyphagous predators and parasitoids, which would otherwise damage crops (Paoletti and Bressan, 1996). It has been reported that removing shelterbelts in rural settings can cause a loss of litter in topsoil and this can lead to a shift of feeding habits among some detritivores such as the case of the slater, *Australiodillo bifrons*, in NSW, Australia, which is becoming a cereal pest (Paoletti *et al*., 2007a; 2007b).

Agriculture intensification, along with the widespread use of chemicals, is also curtailing the benefits provided by pollinators, especially bees (Kremen *et al*., 2002; Biesmeijer *et al*., 2006; Klein *et al*., 2007). This is a critical issue, because although 60% of global production comes from crops that do not depend on animal pollination, still 35% of crop production depends on pollinators (5% are unevaluated yet) (Pimentel *et al*., 1997; Klein *et al*., 2007).

F. The Role of Animal Production

Worldwide, an estimated 2 billion people live partly on a meat-based diet, while an estimated 4 billion people live primarily on a plant-based diet (Pimentel and Pimentel, 2008).

Meat consumption is matter of extensive debate because the environmental impact of livestock is enormous (Rifkin, 1992; Rosegrant *et al*., 1999, Smil, 2000, 2002; Brown, 2005; Naylor *et al*., 2005; FAO, 2006; Fiala, 2008b; Pimentel and Pimentel, 2008; Stokstad, 2010).

It has been estimated that if the world's population today were to eat a Western diet of roughly 80 kg meat per capita per year, the global agricultural land required for production would be about 2.5 billion hectares, two-thirds more than is presently used (Smil, 2002; Keyzr *et al*., 2005; Naylor *et al*., 2005). FAO (2006) estimates that global production of meat and milk will more than double in 2050, with meat rising from 229 million tonnes in 1999/2001 to 465 million tonnes in 2050, and milk from 580 to 1043 million tonnes in the same period.

Livestock production accounts for 70% of all agricultural land and 30% of the land surface of the planet (FAO, 2006). Expansion of livestock production is a key factor in deforestation, especially in Latin America where the greatest amount of deforestation is occurring; 70% of previous forested land in the Amazon is occupied by pastures, and feed crops cover a large part of the remainder. In the United States, with the world's fourth largest land area, livestock are responsible for an estimated 55% of erosion and sediment, 37% of pesticide use, 50% of antibiotic use, and 30% of of the high amount nitrogen and phosphorus contaminating freshwater ecosystems (FAO, 2006; Stokstad, 2010).

FAO (2006) estimates that in 2002 a total of 670 million tonnes of cereals were fed to livestock, representing about 30% of the global cereal harvest. According to Brown (2005), while the consumption of animal protein has grown, that share of the world grain harvest used for livestock feed has remained at about 37%. Among the cereals, FAO (2006) estimates that more than 60% of maize and barley is used mainly as feed. In addition 350 million tonnes of protein-rich processing by-products are used as feed (mainly brans, oilcakes and fishmeal). More than 97% of the soymeal produced globally is also fed to livestock (FAO, 2006). According to Smil (2002), in 1900 just over 10% of the world's grain harvest was fed to animals, most of it going to energize the field work of draft animals rather than to produce meat while in the late 1990s it surpassed 40%, and in the United States it reached 60% in the late 1990s.

In the United States as a whole, about 300 million hectares are in pasture and about 30 million hectares are in cultivated grains for livestock production (USDA, 2007). In addition, to large amount of forage that are unsuitable for human consumption and are fed to livestock, about 323 million tons of grains, or about 816 kg per American are fed to American livestock (USDA, 2007).

It has to be stressed that typical efficiencies of protein production via animal feeding are very wasteful: at least 80% and as much as 96% of all protein in cereal and leguminous grains fed to animals are not converted to edible protein (Smil, 2000, 2002).

Increasing meat consumption would also put significant pressure on water resources. An estimated 2.5–10 times more energy is required to produce the same amount of calorie energy and protein from livestock than grain (Smil, 2000; Molden, 2007; Pimentel and Pimentel, 2008). Meeting daily nutritional energy needs would also require much higher water consumption because meat production requires 4,000–15,000 $\mathrm{l\ kg^{-1}}$, while grain production just 1,000–2,000 $\mathrm{l\ kg^{-1}}$.

Rockstrom *et al.* (2007) estimated water requirement per energy unit at 0.47 $\mathrm{m^3}$ 1,000 $\mathrm{kcal^{-1}}$ for cereals and 4 $\mathrm{m^3}$ 1,000 $\mathrm{kcal^{-1}}$ for meat.

Intensive livestock production has created problems of manure disposal and water pollution, as well as greatly contributing to GHGs emissions (Subak 1999; FAO, 2006; Pimentel and Pimentel, 2008; Koneswaran and Nierenberg, 2008). Subak (1999) estimated that the social costs of the feedlot system for beef production at 15 kg CO_2 equivalent $\mathrm{kg^{-1}}$ beef are more than double that of the pastoralist system. According to estimates from FAO (2006), the amount of fossil fuels burned varies depending on the species and type of animal product. For example, processing 1 kg of beef requires 4.37 megajoules (MJ), or 1.21 kilowatt-hours, and processing 1 dozen eggs requires > 6 MJ, or 1.66 kilowatt-hours. When considering the entire commodity chain, livestock production is estimated to release every year in the atmosphere 6,5 billions of CO_2 -equivalent GHGs, accounting for 18% of GHGs emissions, a bigger share than that of transport (FAO, 2006; Fiala, 2008b) and less than only energy production [according to Fiala (2008b), GHGs emission from human activities are: Energy production 21%; Livestock production 18%; Transportation 14%; Fossil fuel retrieval 12%; Agriculture 12%; Residential 10%; Manufacturing 7%; Land use 4%; Waste disposal and treatment 3%].

In intensive animal production, drugs are often used to speed up fattening and milk production. The use of antibiotics as growth promoters destroys or inhibits bacterial populations.

In the United States (the practice is prohibited in European Union), the injection of bovine growth hormone (BGH) into dairy cattle is reported to increase milk production from10% to 15% in dairy cows (Capper *et al*., 2008), but its effect on human health are still debated.

The high animal stocking rate, together with the high amount of milk production in cows, forces farmers to use antibiotics to lower the risk of epidemics spreading among animals. Livestock in the United States, for instance, are treated with 8 times more antibiotics than the human population (Pimentel and Pimentel, 2008). Such a large use of antibiotics in agriculture poses a threat to human health because it induces the spread of resistance in pathogens and has been a central issue in the medical field for decades (Cohen, 1992; Vaquero and Blázquez, 1997; FAO, 2005; Lipsitch *et al*., 2002; Smith *et al*., 2005). In the United States 70% to 80% of the antibiotics are used in livestock production, causing an estimated death of 5,000 people each year (Pimentel, 2010).

In order to work for a more sustainable agriculture, major actions should be taken concerning animal production and meat consumption in our diets, as it directly affects our impact on the planet and its resources, as well as our health (Subak, 1999; Smil, 2000, 2002; FAO, 2006; Baroni *et al*., 2007; McMichael *et al*., 2007; Fiala, 2008b; Pimentel and Pimentel, 2008).

The matter, however, is far from simple and reducing meat consumption with the view to make cereals more available and cheaper for poor people may not be easily accomplished given the current social expectations. Some scholars (e.g, Rosegrant *et al*., 1999; Stokstad, 2010), for instance, argue that when the farmers produce less meat, demand for corn and soy drops and the grains become more affordable. That may be good for people in the parts of Africa and Latin America where corn is a dietary staple. But people in many developing countries, particularly in Asia, eat rice and wheat as staple food, rather than corn. So, if consumers in developed countries replace meat with pasta and bread, world wheat prices may rise and that may increase malnutrition in developing countries that rely on wheat, such as India. The use of mini-livestock can be less resource-consuming, and if properly managed could represent an alternative to the current livestock production system, especially in tropical countries (Paoletti, 2005; Ochatt and Jain, 2007).

G. Concern for the Future

As pointed out by Foley *et al.* (2005, pp. 570–571) “In short, modern agricultural land use practices may be trading short-term increases in food production for long-term losses, in ecosystem services, including many that are important to agriculture.” Such an impact, however, although too often neglected in the accounting system, when properly assessed turns out to be very costly for society (e.g., Pimentel *et al*., 1995; Pimentel, 1997; Buttel, 2003; Pretty *et al*., 2000; 2003; McCandless *et al*., 2008). Policies aimed at internalizing agricultural externalities would much benefit both resource allocation and natural resource conservation. If the impact of agriculture practices on the soil and the environment cannot be mitigated, in the long run we may pose a serious threat to our living support system and to the food security of a large part of humanity. More research should be carried out in order to improve the efficiency of agricultural systems and reduce their impact on the environment and on natural resources. As stated by NRC (2010) in the case of American agriculture, for instance, only one-third of public research spending is devoted to exploring environmental, natural resource, social, and economic aspects of farming practices.

Agriculture should also aim to guarantee food security for people. As stated by FAO (2008), food security is defined as a state when “all people, at all times, have physical and economic access to sufficient, safe and nutritious food for a healthy and active life.” So, in order to guarantee food security to humanity we have to be concerned with the health of earth’s natural resources, soil fertility to start with. The World Bank in its World Development Report (2008) indicates the urgency of dealing with climate change, and highlights the fact that “Poor people who depend on agriculture are most vulnerable to climate change.” (World Bank, 2008, p. 17).

According to UNEP (2009) up to 25% of the world’s food production may become lost due to environmental breakdown by 2050 unless action is taken. And action is even more urgent when the possible effects of climate change are taken into account: these are likely to hit billions of people in developing countries, mostly those already suffering for food shortages (Parry *et al*., 2007; FAO, 2008; Lobell *et al*., 2008; UNEP, 2009; Barrett, 2010; Godfray *et al*., 2010).

Of course, it would be naïve to believe that our environmental concern is all that matters. We cannot dismiss the importance of social and economic forces as constraints and driving forces affecting food security, such as: access to food (Sen, 1982; Drèze and Sen, 1989), population dynamics (Smil, 1991, 2000; Hardin, 1993; Cohen, 2003), market forces (Patel, 2008), agriculture research (Smil, 2000; Pardey *et al*., 2006; Alston *et al*., 2009), access to credit (Yunus, 2009), subsidies and commodity price distortion (Peterson, 2009; Anderson *et al*., 2010), availability of natural resources (Tilman *et al.*, 2002; Pimentel and Pimentel, 2008; Smil, 2008; UNEP, 2009), production lost in post harvest storage and management (Smil, 2000; PHLIS, 2010).

III. THE CALL FOR SUSTAINABILITY IN AGRICULTURE

The definition of "sustainable agriculture," in its modern approach, can be traced back to the United States in the early 1980s, indicating a way of farming that should mimic natural ecosystems. Within the domain of sustainable agriculture fall some other definitions and practices such as agroecology, integrated agriculture, low input, precision agriculture and organic agriculture (Pretty, 2008). In the last decades, in order to face the challenge to feed 9 billion people by 2050, a concept called "sustainable intensification" has been discussed, meaning producing more food from the same area of land while reducing the environmental impacts (Pretty, 2002; 2008; Royal Society of London, 2009; Godfray *et al*., 2010).

A. Development and Goals of Sustainable Agriculture

The conceptual setting for the definition of sustainable agriculture has been posed by Wes Jackson who is credited to have been the first to use the term "sustainable agriculture" in his publication *New Roots for Agriculture* in 1980 (Harwood, 1990; Kirschenmann, 2004). In a 1983 paper, Rodale proposed the concept of "regenerative agriculture" referring to the need for an agriculture based on the principle of ecological interactions (Harwood, 1990).

The term "sustainable agriculture" did not emerge in popular usage until the late 1980s. Sustainable agriculture must, as defined by the U.S. Department of Agriculture in the 1990 Farm Bill: "... over the long term, satisfy human needs, enhance environmental quality and natural resource base, make the most efficient use of nonrenewable resources and integrate natural biological processes, sustain economic viability, and enhance quality of life." (USDA, 1990). The early idea of a sustainable agriculture was for a farming system that mimics natural ecosystems (e.g., Jackson, 1980; Soule and Piper, 1991; Scherr and McNeely, 2007). We remember also the lesson of Eugene P. Odum (one of the fathers of modern ecology), who in his talks and books made the point that American agriculture has to mimic native forests and prairies to become more sustainable (Odum, 1993). Over time, nature tends to establish more diversity than humans do with most of their agricultural systems. In a productive hectare of agricultural land there may be tens of thousands of species of organisms that weigh up to 10 tons (Lavelle and Spain, 2002; Pimentel, 2006). Thus, agriculture, when properly managed, still can preserve a great deal of biodiversity. Lately the term "ecoagriculture" has also been proposed (e.g., Scherr and McNeely, 2007).

Sustainable agriculture should aim at: preserving the natural resource base, especially soil and water, relying on minimum artificial inputs from outside the farm system, recovering from the disturbances caused by cultivation and harvest while at the same time being economically and socially viable (Poincelot, 1986; Altieri, 1987; Edwards *et al.*, 1990; Soule and Piper, 1991; Dunlap *et al*., 1992; Francis *et al*., 2006; Pimentel *et al*., 2005; Gliessman, 2007). Sustainable agriculture does not refer to a prescribed set of practices and it differs from organic agriculture because, in sustainable agriculture, agrochemicals (synthetic fertilizers and pesticides) may or may not still play a role. However, their use is kept to a minimum or not used at all, and conservative practices (crop rotation, integrated pest management, natural fertilization methods, minimum tillage, biological control) are fully integrated in farm management.

As summarized by Pretty (2008, p. 451) the key principles for sustainability can be summarized as:

(i) integrate biological and ecological processes such as nutrient cycling, nitrogen fixation, soil regeneration, allelopathy, competition, predation and parasitism into food production processes,
(ii) minimize the use of those non-renewable inputs that cause harm to the environment or to the health of farmers and consumers,
(iii) make productive use of the knowledge and skills of farmers, thus improving their self-reliance and substituting human capital for costly external inputs, and
(iv) make productive use of people's collective capacities to work together to solve common agricultural and natural resource problems, such as for pest, watershed, irrigation, forest and credit management.

According to many authors there is much room for improvement toward a more sustainable agriculture, both in developed and developing countries (Smil, 2000; Altieri, 2002; Cassman *et al*., 2002; Jackson, 2002; Pimentel *et al*., 2005; Jordan *et al.*, 2007; Pretty, 2008; Bohlen and House, 2009; Glover *et al*., 2010a). Recent research in the United States, for instance, has demonstrated that organic production of the two most important crops (corn and soybeans) can be produced without commercial nitrogen, without soil erosion, without insecticides or herbicides and with 30% less fossil energy (Pimentel *et al*., 2005). The corn and soybean yields were equal to yields using conventional production methods.

B. Assessing Sustainability: A Complex Issue

For sustainable agriculture, the major challenges to be addressed are (Lowrance *et al*., 1986; Conway, 1987; Hansen, 1996; McConnell and Dillon, 1997; Bland, 1999; Ruttan, 1999; Kropff *et al*., 2001; von Wirén-Lehr, 2001; Altieri, 2002; López-Ridaura *et al*., 2002; Pretty, 2002; Giampietro, 2004; Gomiero *et al*., 2006; Bland and Bell, 2007; Jordan *et al*., 2007; Bohlen and House, 2009):

- The multifunctional nature of agriculture (not only producing commodities, but also preserving the health of ecosystems, consumers and rural communities),

- The multi-scale nature of the complex network of relations among ecosystems and socioeconomic systems, which requires considering simultaneously different but relevant dynamics operating at different hierarchical levels.

However, as already noted by some authors (e.g., Lowrance *et al*., 1986; Hansen, 1996; Park and Seaton, 1996; Giampietro, 2004; Sydorovych and Wossink, 2008), sustainable agriculture means many things to different people, and definitions abound. Goldman (1995), lists fourteen definitions of sustainability in the field of agriculture, and argues, for instance, that the concepts of sustainable agriculture are based mainly on the experiences and norms of western industrial nations and may not be appropriate to sub-Saharan Africa and other developing regions. Beets (1990, p. 723), for instance, referring to subsistence agriculture state that sustainable agriculture is: "The ability of a system to maintain productivity in spite of a major disturbance, such as caused by intensive stress or a large perturbation," and that perfectly fits the needs of subsistence farmers.

What is "sustainable" may be also culture-oriented. For instance, when the Western agriculture package is transferred to other continents, it tends to dismiss, or overlook, many sorts of traditional local resources – such as insects and other arthropods, earthworms, small vertebrates and wild plants (insects and earthworms, for instance, may total more than 3,000 kg/ha; Pimentel and Pimentel, 2008). These local resources can play an important role in guaranteeing food security in poor rural areas, but are often neglected because of the Western perception that these are not "proper food" for people (Paoletti and Bukkens, 1997; Paoletti, 2005; Ochatt and Jain, 2007).

Being a complex issue, "sustainability" depends on the perspective taken when looking at the system. This lead to some key considerations when attempting sustainability assessment (Giampietro, 2004; Gomiero *et al*., 2006):

- Farming systems are not steady-state systems but highly adaptable and evolving systems (*ceteris* are never *paribus*),
- Any representation of these systems depends on a set of choices made by the observer when framing the identity of what is observed,
- It is impossible to reach the best/optimal solution to a problem of sustainability, we should address the issue of "sustainable/optimal for whom and in which sense," as there is no solution that optimizes all the possible criteria of performance for all the relevant actors (who decides who are the relevant actors and how?),
- Any assessment implying a value judgment (such as good or bad) cannot be made by the application of an algorithm within an optimization protocol. Rather, value judgments must be made within a participatory process of multi-criterial assessment,
- When dealing with participatory processes of multi-criterial assessment, it is crucial to be able to guarantee not only the quality of the scientific analysis used for characterizing options and scenarios, but also the quality of the process of participatory assessment itself.

This implies that an adequate representation of a farming system requires a multi-dimensional, or multi-criterial, approach, in which many dimensions (e.g., economic, environmental, social, cultural dimension), and many levels of analysis (e.g., farmers, consumers, governments, international agreements) have to be simultaneously taken into account. This is what can be defined also as "Integrated Assessment" as defined by Rotmans and van Asselt (1996, p. 327): "an interdisciplinary and participatory process combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena" Beddoe *et al.* (2009) discuss even the need to redefine the very institutional structure of society in view to meet the call for sustainability.

Because of its complex, multi-dimensional nature, it is widely recognized that assessing farming systems and agricultural sustainability requires to embrace a number of different scales, criteria and sets of indicators. Such a complex approach has been developed both theoretically (e.g., Lowrance *et al*., 1986; Ikerd, 1993; Wolf and Allen, 1995; Bland, 1999; Morris and Winter, 1999; Kropff *et al*., 2001; von Wirén-Lehr, 2001; Piorr, 2003; Giampietro, 2004; Gomiero *et al*., 2006; Verburg *et al.*, 2006; van Cauwenbergh *et al*., 2007; Sydorovych and Wossink, 2008), as well as applied in a number of case studies both in developed and developing countries (e.g., Beets, 1990; McConnell and Dillon, 1997; Gomiero *et al*., 1997; Beinat and Nijkamp, 1998; Giampietro and Pastore, 1999; Gliessman, 2000; Gomiero and Giampietro, 2001; López-Ridaura *et al*., 2002; Giampietro and Ulgiati, 2005; Gafsi *et al*., 2006; More *et al*., 2007; Groot *et al*., 2007; Janssen and van Ittersum, 2007; van Ittersum *et al*., 2008). The interested reader could refer to Collinson (2000) for a history of farming systems research.

NRC (2010, p. 528) argues that: "To pursue systemic changes in farming systems, research and development have to address multiple dimensions of sustainability (productivity, and environmental, economic, and social sustainability) and to explore agroecosystem properties, such as complex cropping rotations, integrated crop and livestock production, and enhanced reliance on ecological processes to manage pests, weeds, and diseases (recognizing their interconnectedness and interactions with the environment), that could make systems robust and resilient over time."

IV. POSSIBLE ACTIONS TOWARDS A MORE SUSTAINABLE AGRICULTURE

There is an urge to develop more ecological agriculture practices able to preserve soil fertility, reduce the consumption of nonrenewable natural resources and integrated with local biodiversity and landscape. The Millennium Ecosystem Assessment (2005) recommended the promotion of agricultural methods that increase food production without harmful trade-offs from soil erosion, excessive use of water, nutrients, or pesticides. FAO (2002; 2003; 2004) also stressed the need to reduce the environmental impact of agriculture practice as it poses a risk to the sustainability of agriculture and food security itself.

In the last decades, a number of different philosophical approaches to agriculture management and novel agronomic techniques have been proposed and implemented in order to meet the demand for a more sustainable agriculture. Here we list the main approaches in alphabetic order.

A. Agroecology

The use of the term agroecology can be traced back to the 1930s (Wezel *et al.*, 2009), and by the 1980s had reached a broad diffusion. The scales and dimensions of agroecological investigations changed over the past 80 years from the plot and field scale to the farm and agroecosystem scale.

In the 1980s some scholars argued that in order to move towards a more sustainable agriculture a whole-farm holistic approach needed to be embraced. Such an approach stands at the basis of the science of agroecology (Altieri *at al.*, 1983; Altieri, 1987; 2002; Conway, 1987; Gliessman, 1990). As defined by Altieri (2002, p. 8, bold in original) "**Agro-ecosystems** are communities of plants and animals interacting with their physical and chemical environments that have been modified by people to produce food, fiber, fuel and other products for human consumption and processing. **Agro-ecology** is the holistic study of agro-ecosystems including all the environmental and human elements. It focuses on the form, dynamics and functions of their interrelationship and the processes in which they are involved." Lately the term agroecology has been used to in include the agrifood system (see Francis *et al.* this issue).

The new concept and approach found wide audience among scholars, and established agroecology as a respected scientific field in its own right (Paoletti *et al.*, 1989; Carrol *et al.*, 1990; Altieri, 2002; Francis *et al.*, 2003; Altieri and Nicholls, 2004; Giampietro, 2004; Wojtkowski, 2006; Gliessman, 2007; Bohlen and House, 2009; Wezel and Soldat, 2009; Wezel *et al.*, 2009).

According to Wezel *et al.* (2009), three approaches can be distinguished: (1) investigations at plot and field scale, (2) investigations at the agroecosystem and farm scale, and (3) investigations covering the whole food system.

In order to properly study agroecosystem functioning and management, integrated scale analysis has to be performed along with the multiple scales and dimensions of agrosystems (Conway, 1987; Lowrance *et al.*, 1986; McConnell and Dillon, 1997; Gomiero *et al.*, 1997; 2006; Bland, 1999; Kropff *et al.*, 2001; Altieri, 2002; López-Ridaura *et al.*, 2002; Giampietro, 2004; Bland and Bell, 2007; Vadrevu *et al.*, 2008).

B. Agriculture Intensification

With world food demand doubling by 2050, how to preserve natural habitats will become a critical challenge. Two competing solutions are proposed: (1) a wildlife-friendly farming, which boosts densities of wild populationson farmland but may decrease agricultural yields; and (2) land sparing, which minimizes demand for farmland by increasing yield by improving crop efficiency (Trewavas, 2001; Pretty, 2002; 2008; Tilman *et al.*, 2002; Cassman *et al.*, 2003; Green *et al.*, 2004; Burney *et al.*, 2010). The term "eco-efficiency" has been used by some scholars (Groot *et al.*, 2007; Wilkins, 2008; Keating *et al.*, 2010; Lal, 2010) to address the interrelationships and trade-offs among a host of production, conservation, economic, and social values at landscape scale.

Some authors (e.g., Cassman *et al.*, 2003) warn that although harvested cereal production area has remained relatively constant during the past 20 years, evidence of yield stagnation in several major cropping systems will make it increasingly difficult to sustain increases in food production without an expansion in cultivated areas. They conclude that increased nitrogen use and water use efficiency, and improved soil quality, are key factors in order to avoid expansion of cultivation into natural ecosystems, while meeting human needs. However, such an issue is very complex and simple models, which, for instance, claim that technological advance can lead to sparing land has been proved untrue in a number of cases (García-Barrios *et al.*, 2009; Perfecto and Vandermeer, 2010). Perfecto and Vandermeer (2010), for instance, in the case of tropical agriculture and forest conservation, claim that social context makes a difference in the direction as well as the degree of impact of agricultural intensification on deforestation.

However, whether increasing agriculture intensity (crops yield) results in a reduction of cultivated land is a matter of debate, as some authors do not find any correlation between agriculture intensification and sparing land (e.g., Ewers *et al.*, 2009; Rudel *et al.*, 2009). Ewers *et al.* (2009), for instance, argue that in developing countries there is a tendency for the area used to grow crops other than staples to increase in the countries where staple crop yields increased. There remained a weak tendency in developing countries for the per capita area of all cropland to decline as staple crop yield increased, a pattern that was most evident in developing countries with the highest per capita food supplies. In developed countries, there was no evidence that higher staple crop yields were associated with decreases in per capita cropland area.

C. Integrated Agriculture

Integrated agriculture is a farming method that combines management practices from conventional and organic agriculture. As an example, animal manure may be used instead of chemical fertilizer when possible. Pest management (integrated pest management) is carried on combining several methods: using crop rotation, the release of parasitoids, cultivating pest-resistant varieties, and using various physical techniques, leaving pesticides as the last resort (Edens, 1984; Poincelot, 1986; Pimentel, 1997; Mason, 2003; Pretty, 2005; Altieri and Nicholls, 2004; Francis *et al*., 2006).

Weeds can be managed through tillage and cultivation practices, using competitive cultivars, crop diversification and other factors can be used to reduce weed germination, growth, competitive ability, reproduction, and dispersal. Introducing arthropod and microbial biocontrol agents can also be successfully employed (Altieri, 1987; Pimentel, 1997; Liebman *et al.*, 2001; Lampkin, 2002; Gliessman, 2007). Integrated agriculture is not governed by specific regulations but its goal is still to reduce as much as possible both farm management costs and its environmental impact, aiming at the long term sustainability of farming practices.

D. Organic Agriculture

A different alternative to sustainable agriculture has been proposed and implemented by the organic agriculture movement. Although sustainable agriculture practices are adopted by an increasing number of farmers only organic agriculture is regulated by laws and needs to strictly follow a specific set of norms. Such norms, among other, forbid the use of agrochemicals and strictly regulate the use of drugs in animal rearing; they also forbid the use of GMO. Because of this topic will be widely dealt with in a specific paper in this issue (see Gomiero *et al*., this issue), in this section we will give just a very brief introduction.

The organic movement appeared in Europe in the 1920s and in the United States in the 1940s representing farmers and citizens refusing the use of agrochemicals, and willing to persevere with traditional agricultural practices (Conford, 2001; Lotter, 2003; Lockeretz, 2007). The organic movement has national and international representatives. The International Federation of Organic Agriculture Movements (IFOAM), is based in Bonn, Germany (http://www.ifoam.org/).

Organic agriculture has been officially recognized by the European Union in 1991 and by the America federal government in 1995. Internationally, the Codex Commission approved the Codex Guidelines for plant production in June 1999, followed by animal production in July 2001. The Codex Alimentarius Commission at point 5 states that: “Organic Agriculture is one among the broad spectrum of methodologies which are supportive of the environment. Organic production systems are based on specific and precise standards of production which aim at achieving optimal agroecosystems which are socially, ecologically and economically sustainable.” (Codex Alimentarius, 2004, p. 4).

Organic agriculture other than crops productivity aims at preserving soil fertility, reducing soil erosion, conserving water, biodiversity, landscape, ecological functionality, and reducing global change (Reganold *et al.*, 1987; FAO, 2002; 2004; Mäder *et al*., 2002; Pimentel *et al*., 2005; Kristiansen *et al*., 2006; Niggli *et al*., 2009; Crowder *et al*., 2010).

Organic agriculture can represent a valuable option in order to work for a more sustainable agriculture, and deserves wide experimentation to fully explore and understand its potentialities as well as constraints and limitations.

E. Permaculture

Mollison and Holmgren, in their book *Permaculture One: A Perennial Agriculture for Human Settlements* (Mollison and Holmgren, 1978) coined the term “*permaculture*”, a contraction of “permanent agriculture.” Permaculture puts the emphasis on management design and on the integration of the elements in a landscape, considering the evolution of landscape over time. The goal of permaculture is to produce an efficient, low-input integrated culture of plants, animals, people and structure, and integration that is applied at all scales from home garden to large farm (see also http://www.permaculture-info.co.uk/). However, one problem with permaculture is that biomass from surrounding areas is used to fertilize the permaculture areas. Thus, this is depleting resources in the surrounding areas.

F. Precision Agriculture

Precision agriculture (also known as “precision farming,” “site-specific crop management,” “prescription farming,”and “variable rate technology”) has developed since the 1990s, and refers to agricultural management systems carefully tailoring soil and crop management to fit the different conditions found in each field. Precision agriculture is an information and technology based agricultural management system (e.g., using remote sensing, geographic information systems, global positioning systems and robotics) to identify, analyze and manage site-soil spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment (Lowenberg-DeBoer, 1996; National Research Council, 1998; Srinivasan, 2006; Gebbers and Adamchuk, 2010). Precision agriculture is now taught in many universities around the world (see for instance http://precision.agri.umn.edu/links.shtml).

G. Perennial Crops

Because of the dramatic consequences of plowing on soil conservation, in the United States since the 1980s some authors (Jackson, 1980; 2002; Soule and Piper, 1991; Glover, 2005; Glover *et al*., 2007, 2010a; 2010b) began suggesting to move from an agriculture based on annual crops to an agriculture relying on the cultivation of perennial crops, so that the detrimental effect of soil tillage and agrochemical usage could be avoided or at least greatly reduced.

Perennial crops [e.g., Intermediate wheatgrass (*Thinopyrum intermedium*) and other perennial *Th*. species, Maximilian sunflower (*Helianthus maximiliani*), Illinois bundleflower (*Desmanthus illinoensis*) and Flax (a perennial species of the *Linum* genus)] have been proposed in order to reduce nitrogen loss and improve soil conservation. Perennial crops, with their roots exceeding depths of two meters, can improve ecosystem functions, such as water conservation, nitrogen cycling and carbon sequestration; more than 50% when compared to conventional crops. Perennial crops are reported to be 50 times more effective than annual crops in maintaining topsoil, reduce N losses from 30 to 50 times, and store about 300 up to 1,100 kg C/ha per year compare to 0 to 300–400 kg C/ha per year as do annual crops. It is believed they could help restrain climate change (Cassman *et al*., 2002; Cox *et al*., 2005; Glover *et al*., 2007; 2010a; 2010b).

Management costs are also reduced because perennial crops do not need to be replanted every year, so they require fewer passes of farm machinery and fewer inputs of pesticides and fertilizers as well, which reduces fossil-fuel use. Glover *et al*. (2007) report that herbicide costs for annual crop production may be 4 to 8.5 times the herbicide costs for perennial crop production, so fewer inputs in perennial systems mean lower cash expenditures for the farmer.

Perennial crops are predicted to better adapt to temperature increases as the magnitude predicted by most climate-change models. Cassman *et al*. (2002) report that increases of 3 to 8 degrees Celsius are predicted to increase yields of switchgrass (*Panicum virgatum*), a perennial forage and energy crop, by 5,000 kg per ha, whereas for annual species yields are predicted to decline (e.g., maize, −1,500 kg per ha; soy-bean, -800 kg per ha; sorghum, -1000 kg per ha).

H. Transgenic Technology

Technological advancements in the field of genetics have made it possible to manipulate gene expression and operate gene transfers from an organism to another. Such possibility opened the doors for a wide number of practical applications, mainly in medicine and agriculture.

It is beyond the scope of the present paper to provide a review of genetic engineering in agriculture and related debates on social, political and ethical issues (e.g., patenting life and intellectual property rights, biopiracy, biosafaty and the precautionary principle). However, because of its relevance on agriculture sustainability we wish to briefly introduce the topic.

Genetic Modified Organism (GMO) or Transgenic Organisms (TO) are considered by many a chance to meet the food demand while at the same time preserving the environment and limiting agriculture environmental impact. According to many authors GMOs can represent a new “green revolution”, especially for developing countries facing food scarcity, as they could be able to boost agriculture productivity and cope with new environmental challenges, such as climate change and soil exhaustion, while at the same time benefiting the conservation of natural resources (Conway, 1997; Ejeta, 2010; Enserink, 2010; Fedoroff *et al*., 2010; Gilbert, 2010).

Crops, could, for instance, be engineered to resist pest, improve water use efficiency, cope with drought or salty soil, self fix N, or to produce more or novel important nutritional elements (e.g., the case of golden rice, Enserink, 2010) (Conway, 1997; Chrispeels and Sadava, 2002; Hails, 2002; Hahlbrock, 2007; Murphy, 2007; Ferry and Gatehouse, 2009; Royal Society of London, 2009; Fedoroff *et al*., 2010; Gilbert, 2010; Pennisi, 2010; Tester and Langridge, 2010).

In Bt corn, a toxin-encoding gene from the bacterium *Bacillus thuringiensis* has been successfully transferred to corn to defend it from stem borer (*Ostrinia nubilalis*), a major corn pest. Crops can also be engineered to be resistant to herbicides; in this way weeds can be reduced without affecting crops. Such is that case, for instance, of soybean tolerant to the herbicide Round Up®. About 90% of U.S. corn and soybeans are herbicide tolerant [in the United States, since the introduction of herbicide-tolerant plants, the use of herbicides has been reported to be increasing (Benbrook, 2009), and the excessive use of herbicides can have a negative impacts on the environment].

According to the International Service for the Acquisition of Agri-biotech Applications (ISAAA, 2010), the use of plant transgenics is the fasted adopted crop technology: in 2009 there were 134 million ha of biotech crops, with an underlying 80-fold land increase from 1996 to 2009 and a year-to-year growth of 9 million hectares or 7% on average. Developing countries have increased their share of global biotech crops to almost 50% and are expected to continue to significantly increase biotech hectarage in the future. Figures supplied by ISAAA (2010) for 2009 indicate that Round Up® soybean is the principal biotech crop, accounting for 69.2 million ha or 52% of global biotech crop area (65.8 million ha in 2008), followed by Bt maize (41.7 million hectares or 31%, 37.3 million ha in 2008), Bt cotton (16.1 million hectares or 12%, 15.5 million ha in 2008) and Round Up® canola (6.4 million hectares or 5%, 5.9 million ha in 2008).

While GMOs such as Bt corn and cotton, and herbicide-tolerant soybean have been cultivated in USA since 1990s, most of the European countries are still against their approval for cultivation. In Europe the environmental release of GMO, generated an extensive and intense social and political debate, concerning the environment and food safety and the ethical acceptability of engineered crops (Wolfenbarger and Phifer, 2000; Hails, 2002; Altieri *et al.*, 2004; Borlaug, 2007; Stokstad, 2008; Waltz, 2009), and a precautionary approach to their release has been invoked by some stakeholders (Aslaksen and Ingeborg Myhr, 2007). It has to be pointed out that the use of GM technology in medical screening and therapy is not met with the same level of hostility, and this holds true even amongst radical environmentalist movements.

Some researchers hold that even organic farming could benefit from using transgenic crops because of the benefit for the environment and reduction of farming costs (Amman, 2008). Some authors (e.g., Stone, 2002) criticize the fact that genetic research is mostly in private hands, and does not pursue what may really benefit the poor: the genetic improvement of staple-subsistence crops, such as: cassava (*Manihot esculenta*), sorghum, pearl millet, because of companies could not make money out of that.

Environmental risks directly related GMO cropping concerns two main issues: (1) the effect of gene flow to non target organisms, and (2) the probability of gene flow to relative wild plants (leading, for instance, to weed resistance to herbicides) (Ellstrand, 2003; Chandler and Dunwell, 2008; Romeis *et al*., 2008). A further issue concerns the development of resistance in weeds and pests, as happened with agrochemicals.

Concerning the first issue, it is reported that large international initiatives are already under way to develop a scientifically rigorous approach to evaluate the potential risks to non target arthropods posed by insect-resistant and genetically modified crops (Romeis *et al*., 2008).

Transgene flow (introgression) from GRCs to non-GM crops or wild weeds is the largest risk posed by glyphosate resistant crops (GRCs). Glyphosate resistance transgenes have been found in fields of canola that was supposed to be non-transgenic (Cerdeira and Duke, 2006).

Spread of weeds and pests resistance is an issue that deserves much attention. It has been reported that about a dozen different varieties of weeds are known to have developed resistance to glyphosate, and that the spread of resistance to new weed species is increasing in countries like the United States, Argentina, South Africa, Israel, and Australia (Cerdeira and Duke, 2006; Service, 2007; Phelan, 2009; Nandula, 2010). Pest resistance in Bt cotton has also been reported in the United States (Tabashnik *et al.*, 2009). According to some authors, resistance spread could be overcome by improving regulatory systems and adopting genetic techniques that can find wider approval among the public (Fedoroff *et al*., 2010; Tester and Langridge, 2010).

Pest ecology is a very complex issue, and our knowledge of the matter is still quite limited. Transgenic crops should not to be considered a magic bullet for pest control (Lu *et al*., 2010).

For instance, whenever a primary pest is targeted and controlled, other species are likely to rise in its place. It has been reported, for example, that the boll weevil (*Anthonomous grandis*) was once the main worldwide threat to cotton. As farmers sprayed pesticides against the weevils, bollworms (*Pectinophora gossypiella*) developed resistance and rose to become the primary pest. Similarly, stink bugs *Euschistus servus* (Say), *E. tristigmus* (Say), *Acroster numhilare* (Say), *Nezara viridula* (L.), and leaf-footed bugs such as *Leptoglossus spp.* (primarily *L. phyllopus*) have recently grown back again to be important primary pests of most fruit, nut, vegetable and grain/seed crops in the Southeast and other areas of the United States. Since Bt cotton was introduced, they have replaced bollworms as the primary pest in southeastern United States (Hollis, 2006; Benbrook, 2009; VV. AA. 2009; Qiu, 2010). Use of refugia may help to prevent the spread of resistance (Tabashnik *et al*., 2008). Refugia work by maintaining populations of susceptible insects, some of which will mate with resistant insects, thereby diluting the presence of *Bt*-resistant genes in insect populations. However, refugia contamination has also been reported (e.g., Chilcutt and Tabashnik, 2004) and vigilance should be maintained to make sure that farmers comply with the recommendations given on this matter by the agronomists.

The recent experience with Bt cotton in China should be of concern. More than 4 million hectares of Bt cotton are grown in China. Bt cotton was planted in order to fight the bollworm *Helicoverpa armigera*. However, since the introduction of Bt cotton and the ensuing reduction in pesticide use, the numbers of mirid bugs (insects of the Miridae family), which are not susceptible to the Bt toxin, from being only minor pests in northern China in 1997, have increased 12-fold. Mirids are now becoming a major pest in the region, reducing cotton yields by up to 50% in the absence of further pest control. Moreover, differently from bollworms, mirid bugs are also a threat to crops such as green beans, cereals, vegetables and various fruits (Lu *et al*., 2010), resulting in the new pest causing an overall greater crop and economic loss.

According to some authors (e.g., Kiers *et al*., 2008), GM technology is not to be rejected on principle. Its contribution being promising in some contexts, unpromising in others, and unproven in many more. For instance, genetic engineering may prove beneficial is in the development of annual grains becoming perennial grains. Naturally occurring genes that permit exchange of DNA between chromosomes of different species or genera can be used to obtain offspring with desirable traits from both parents. Plant breeders can use genetic modification to introduce new genes, to modify existing genes, or to interfere with gene expression in specific cases (Glover *et al*., 2010b).

Chrispeels and Sadava (2002) point out that GM technology can play an important role in enhancing agriculture performances and benefit humanity. At the same time, they highlight also that in a world of plenty, distribution of food, and not its production, is the main culprit for current hunger and malnutrition.

V. CONCLUSION

In this paper we have examined some issues concerning the environmental impact of current agricultural practices. Warnings are issued by many experts, regarding the high impact that current agricultural practices are posing on the environment and on long-term soil fertility.

Moving our agriculture toward a more sustainable path is not an easy task, because we need to simultaneously deal with a number of different environmental, social, economic, technical issues, and tackle these at many different levels, from individual farms to the global agro-food system.

We presented a number of alternative agricultural practices that can be adopted, to make agriculture less environmentally damaging, reducing the use of natural resources and preserving soil fertility and biodiversity.

We think that there is room for a different and more ecological agriculture and that research should be conducted in order to better assess the potential and the constraints of the different options available to us.

Eventually, however, it might be required of our society that it changes some of its paradigms and "values" in order to preserve our support system, the soil and its health, for the future generations.

ACKNOWLEDGEMENTS

We wish to thank Prof. Deborah Stinner, Dept. of Entomology, Ohio Agriculture Research and Development Center, The Ohio State University, for her valuable comments which helped to improve the manuscript, and Dr. Lucio Marcello, Glasgow Biomedical Reserach Center, University of Glasgow, for helping to edit the manuscript.

REFERENCES

Allan, J. A. 1998. Virtual water: A strategic resource. Global solutions to regional deficits. *Groundwater* **36:** 545–546.

Allison, F. E. 1973. *Soil Organic Matter and Its Role in Crop Production*. Elsevier, Amsterdam.

Altieri, M. A. 2002. Agroecology: The science of natural resource management for poor farmers in marginal environments. *Agric., Ecosys. & Environ.* **93:** 1–24.

Altieri, M. A., Gurr, G. F., and Wratten, S. D. 2004. Genetic engineering and ecological engineering: a clash of paradigms or scope for synergy? **In**: *Ecological Engineering for Pest Management: Advances in Habitat Manipulation for Arthropods*. pp. 13–31. Gurr, G. F., Wratten, S. D., and Altieri, M. A. Eds., CSIRO Publishing. http://www.biocontrol.ucr.edu/irvin/Ecological%20Engineering%20-%20Gurr%20etal.pdf Accessed on 12 May 2010.

Altieri, M. A., Letpourneau, D. K., and Davis, J. R. 1983. Developing sustainable agroecosystems. *Bioscience* **33:** 45–49.

Altieri, M. A., and Nicholls, C. I. 2004. *Biodiversity and Pest Management in Agroecosystems.* (2nd ed.) CRC Press, Boca Raton, FL, USA.

Amman, K. 2008. Integrated farming: Why organic farmers should use transgenic crops. *New Biotechnology* **25:** 101–107.

Andow, D. A., and Zwahlen, C. 2006. Assessing environmental risks of transgenic plants. *Ecol. Letts* **9:** 196–214.

Aslaksen, I., and Ingeborg Myhr, A. 2007. "The worth of a wildflower": Precautionary perspectives on the environmental risk of GMOs. *Ecological Economics* **60:** 489–497.

Barrows, H. L., and Kilmer, V. J. 1963. Plant nutrient losses from soils by water erosion. *Adv. Agron*. **15:** 303–315.

Beddoe, R., Costanza, R., Farley, J., and other ten authors. 2009. Overcoming systemic roadblocks to sustainability: The evolutionary redesign of worldviews, institutions, and technologies. *PNAS* **106:** 2483–2489.

Beets, W. C. 1990. *Raising and Sustaining Productivity of Smallholder Farming System in the Tropics.* AgBe Publishing, Alkmaar, The Netherlands.

Beinat, E., and Nijkamp, P. (Eds.) 1998. *Multicriteria Analysis for Land-Use Management.* Kluwer Academic Publisher, Dordrecht, The Netherlands.

Benbrook, C. 2009. Impacts of genetically engineered crops on pesticide use: The first thirteen years. The Organic Center. http://www.organiccenter.org/science.pest.php?action=view&report_id=159 Accessed on 12 March 2010.

Berhe, A., Harte, J., Harden, J., and Torn, M. 2007. The significance of the erosion-induced terrestrial carbon sink. *BioScience* **57:** 337–346.

Bianchi, F.J.J.A., Booij, C. J. H., and Tscharntke, T. 2006. Sustainable pest regulation in agricultural landscapes: A review on landscape composition, biodiversity and natural pest control. *Proc. R. Soc. B* **273**: 1715–1727.

Boerboom, C., and Owen, M. 2006. Fact about glyphosate resistant weeds. The Glyphosate, Weeds, and Crops Series. http://www.extension.purdue.edu/extmedia/GWC/GWC-1.pdf Accessed on 12 May 2010.

Bohlen, P. J., and House, G. (Eds.) 2009. *Sustainable Agroecosystem Management*. CRC Press, Boca Raton, FL, USA.

Borlaug, N. 2007. Feeding a hungry world. *Science* **318:** 359.

Bot, A. 2005. *The Importance of Soil Organic Matter: Key to Drought-Resistant Soil and Sustained Food Production*. FAO, Rome. http://www.fao.org/docrep/009/a0100e/a0100e00.htm#Contents Accessed on 20 June 2009.

Brown, L. 2005. *Outgrowing the Earth*. Earthscan, London. Available at http://www.earth-policy.org/index.php?/books/out/out_table_of_contents

Carrol, C. R., Vandermeer, J. H., and Rosset, P. M. (Eds.) 1990. *Agroecology*. McGraw-Hill, New York.

Cerdeira, A. L., and Duke, S. O. 2006. The current status and environmental impacts of glyphosate-resistant crops: A review. *J. Environ. Qual*. **35:** 1633–1658.

Chilcutt, C. F., and Tabashnik, B. E. 2004. Contamination of refuges by *Bacillus thuringiensis* toxin genes from transgenic maize. *PNAS* **101:** 7526–7529.

Chrispeels, M. J., and Sadava, D. E. (Eds.) 2002. *Plants, Genes, and Crop Biotechnology.* Jones and Bartlett Publishers, Inc. London, 2 ed.

Cleveland, C. C., Townsend, A. R., et al. 1999. Global patterns of terrestrial biological nitrogen (N_2) fixation in natural ecosystems. *Global Biogeochemical Cycles* **13:** 623–645.

Codex Alimentarius. 2004. G*uidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods* (GL 32 – 1999, Rev. 1 – 2001). Internet http://www.codexalimentarius.net/web/standard_list.do?lang=en. Accessed on November 24, 2007.

Cohen, M. L. 1992. Epidemiology of drug resistance: Implications for a post-antimicrobial era. *Science* **257:** 1050–1057.

Colborn, T., Dumanoski, D., and Meyers, J.P. 1997. *Our Stolen Future: How We Are Threatening Our Fertility, Intelligence and Survival. A Scientific Detective Story*. Plume, Penguin Books New York.

Collinson, M. P. (Ed.) 2000. *A History of Farming Systems Research*. CAB International, Wallingford, and FAO.

Conford, P. 2001. *The Origins of the Organic Movement*. Floris Books, Glasgow, UK.

Conway, G. R. 1997. *The Doubling Green Revolution: Food for All in the 21st Century*. Penguin, London.

Crowder, D. W., Northfield, T. D., Strand, M. R., and Snyder, W. E. 2010. Organic agriculture promotes evenness and natural pest control. *Nature* **466:** 109–112.

Dalton, H., and Brand-Hardy, R. 2003. Nitrogen: The essential public enemy. *J. Appl. Ecol.* **40:** 771–781.

Edwards, C. A., Lal, R., Madden, P., Miller, R. H., and House, G. (Eds.) 1990. *Sustainable Agricultural Systems*. Soil and Water Conservation Society, Ankeny, Iowa.

Eickhout, B., Bouwman, A.F., and van Zeijts, H. 2006. The role of nitrogen in world food production and environmental sustainability. *Agric. Ecosys. & Environ.* **116:** 4–14.

Ejeta, G. 2010. African green revolution needn't be a mirage. *Science* **327:** 831–832.

Ellstrand, N. C. 2003. Current knowledge of gene flow in plants: Implications for transgene flow. *Phil. Trans. B* **358:** 1163–1170.

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z., and Winiwarter, W. 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience* **1:** 636–639.

Ewers, R.M., Scharlemann, J.P.W., Balmford, A., and Green, R. E. 2009. Do increases in agricultural yield spare land for nature? *Global Change Biology* **15:** 1716–1726.

FAO. 2002. *Organic Agriculture, Environment and Food Security*. Environment and Natural Resources Service Sustainable Development Department. http://www.fao.org/DOCREP/005/Y4137E/y4137e00.htm#TopOfPage. Accessed on 12 January 2009.

FAO. 2004. *The Scope of Organic Agriculture, Sustainable Forest Management and Ecoforestry in Protected Area Management*. FAO, Rome. http://www.fao.org/docrep/007/y5558e/y5558e00.htm#toc. Accessed on November 15, 2009.

FAO. 2005. Antibiotic Growth-Promoters in food animals. http://www.fao.org/DOCREP/ARTICLE/AGRIPPA/555_EN.HTM Accessed on 20 March 2010.

FAO. 2009. FAO: Statistics. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/corp/statistics/en/

FAO. 2010. *The State of Food Insecurity in the World Addressing Food Insecurity in Protracted Crises*. Fao, Rome, http://www.fao.org/docrep/013/i1683e/i1683e.pdf Accessed on 2 November 2010.

Fedoroff, N. V., Battisti, D. S., Beachy, R. N., Cooper, P. J. M., Fischhoff, D. A., Hodges, C. N., et al. 2010. Radically rethinking agriculture for the 21st century. *Science* **327:** 833–834.

Ferry, N., and Gatehouse, A.M.R. (Eds). 2009. *Environmental Impact of Genetically Modified Crops*. CABI, Wallingford, UK.

Fiala, N. 2008a. Measuring sustainability: Why the ecological footprint is bad economics and bad environmental science. *Ecological Economics* **67:** 519–525.

Fiala, N. 2008b. Meeting the demand: An estimation of potential future greenhouse gas emissions from meat production. *Ecological Economics* **67:** 412–419.

Fowler, C., and Hodgkin, T. 2005. Plant genetic resources for food and agriculture: Assessing global availability. *Annu. Rev. Env. Resour.* **29:** 143–179.

Francis, C., Lieblein, G., Gliessman, S., Breland, T.A., Creamer, N., Harwood, R., et al. 2003. Agroecology: The ecology of food systems. *J. Sust. Agric.* **22:** 99–118.

Gafsi, M., Legagneux, B., Nguyen, G., and Robin, P. 2006.Towards sustainable farming systems: Effectiveness and deficiency of the French procedure of sustainable agriculture. *Agricultural Systems* **90:** 226–242.

Gebbers, R., and Adamchuk, V. I. 2010. Precision agriculture and food security. *Science* **327:** 828–831.

Giampietro, M. 2004. *Multi-Scale Integrated Analysis of Agroecosystems*. CRC Press, Boca Raton, FL, London.

Giampietro, M., and Pastore, G. 1999. Multidimensional reading of the dynamics of rural intensification in China: the AMOEBA approach. *Crit. Rev. Plant Sci.* **18:** 299–330.

Giampietro, M., and Ulgiati, S. 2005. An integrated assessment of large-scale biofuel production. *Crit. Rev. Plant Sci.* **24:** 1–20.

Gilbert, N., 2010. Inside the Hothouses of Industry. *Nature* **466:** 548–551.

Gliessman, S. R. (Ed.) 1990. *Agroecology. Researching the Ecological Basis for Sustainable Agriculture.* Spinger-Verlag, New York.

Gliessman, S. R. (Ed.) 2000. *Agroecosystem Sustainability-Developing Practical Strategies.* CRC Press, Boca Raton, FL, USA.

Gliessman, S. R. 2007. *Agroecology. The Ecology of Sustainable Food System.* CRC Press, Boca Raton, FL, USA.

Glover, J. 2005.The necessity and possibility of perennial grain crops. *Renewable Agriculture and Food Systems* **20:** 1–4.

Glover, J. D., Cox, C. M., and Reganold, J. P. 2007. Future farming: A return to roots? *Scientific American* **August:** 83–89.

Glover, J. D., Culman, S. W., DuPont, T., Broussard, W., et al. 2010a. Harvested perennial grasslands provide ecological benchmarks for agricultural sustainability. *Agric. Ecosys. & Environ.* **137:** 3–12.

Glover, J. D., Reganold, J. P., Bell, L. W., Borevitz, J. et al. 2010b. Increased food and ecosystem security via perennial grains. *Science* **328:** 1638–1639.

Goldman, A. 1995. Threats to sustainability in African agriculture: searching for appropriate paradigms. *Human Ecology* **23:** 291–315.

Gomiero, T., and Giampietro, M. 2001. Multiple-Scale Integrated Analysis of farming systems: The Thuong Lo commune (Vietnamese uplands) case study. *Population and Environment* **22:** 315–352.

Gomiero, T., and Giampietro, M. 2005. Graphic tools for data representation in Integrated Analysis of farming system: Attempting an overview. *Int. J. of Global Environ. Issues* **5:** 264–301.

Gomiero, T., Giampietro, M., Bukkens, S. M., and Paoletti, G.M. 1997. Biodiversity use and technical performance of freshwater fish culture in different socio-economic context: China and Italy. *Agric. Ecosys. & Environ.* **62:** 169–185.

Gomiero, T., Giampietro, M., and Mayumi, K. 2006. Facing complexity on agroecosystems: A new approach to farming system analysis. *Int. J. of Agricultural Resources, Governance and Ecology* **5:** 116–144.

Green, R. E., Cornell, S. J., Scharlemann, J.P.W., and Balmford, A. 2004. Farming and the fate of wild nature. *Science* **307:** 550–555.

Groot, J.C.J., Rossing, W.A.H., Jellema, A., Stobbelaar, D. J., Renting, H., and van Ittersum, M. K. 2007. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality - A methodology to support discussions on land-use perspectives. *Agric. Ecosys. & Environ*. **120:** 58–69.

Haberl, H., Krausmann, F., Erb, K. H., Schulz, N. B., Rojstaczer, S., Sterling, S. M., and Moore, N. 2002. Human appropriation of net primary production. *Science* **14:** 1968–1969.

Hails, R. S. 2002. Assessing the risks associated with new agricultural practices. *Nature* **418:** 685–688.

Hansen, J. W. 1996. Is agricultural sustainability a useful concept? *Agricultural Systems* **50:** 117–143.

Harwood, R. R. 1990. A history of sustainable agriculrure. **In**: *Sustainable Agricultural Systems*. pp. 3–19. Edwards, C.A., Lal, R., Madden, P., Miller, R.H., and House, G. Eds., Soil and Water Conservation Society, Ankeny, Iowa.

Hazell, H., and Wood, S. 2008. Drivers of change in global agriculture. *Phil. Trans. B* **363:** 495–515.

Hillel, D., and Rosenzweig, C. 2005. The role of biodiversity in agronomy. *Advances in Agronomy* **88:** 1–34.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., and Mekonnen, M. M. 2009. *Water Footprint Manual: State of the Art 2009*. Water Footprint Network http://www.waterfootprint.org/downloads/WaterFootprintManual2009.pdf Accessed on 23 February 2010.

Hollis, P. 2006. Stink bug dominates in Southeast cotton. Southeast Farm Press. http://southeastfarmpress.com/mag/farming_stink_bug_dominates/ Accessed on 24 June 2010.

Ikerd, J. E. 1993. The need for a system approach to sustainable agriculture. *Agric. Ecosys. & Environ.* **46:** 147–160.

Imhoff, M. L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., and Lawrence, W. T. 2004. Global patterns in human consumption of net primary production. *Nature* **429:** 870–873.

ISAAA. 2010. Global status of commercialized biotech/GM crops: 2009. The first fourteen years, 1996 to 2009. ISAAA Brief 41–2009: Executive Summary. http://www.isaaa.org/resources/publications/briefs/41/executivesummary/default.asp Accessed on 20 June 2010.

Jackson, L., Bawa, K., Pascual, U., and Perrings, C. 2005. *agroBIODIVERSITY: A New Science Agenda for Biodiversity in Support of Sustainable Agroecosystems* (dIVERSITAS, 2005). http://www.agrobiodiversity-diversitas.org/documents/Jackson%20et%20al%20Science%20plan%20agroBIODIV ERSITY.pdf Accessed on 15 May 2010.

Jackson, W. 1980. *New Roots for Agriculture*. University of Nebraska Press.

Jackson, W. 2002. Natural systems agriculture: A truly radical alternative. *Agric. Ecosys. & Environ.* **88:** 111–117.

Janssen, S., and van Ittersum, M. K. 2007. Assessing farm innovations and responses to policies: A review of bio-economic farm models. *Agricultural Systems* **94:** 622–636.

Jordan, N, Boody, G., Broussard, W., Glover, J. D., et al. 2007. Sustainable development of the agricultural bio-economy. *Science* **316:** 1570–1571.

Kelly, B. C., Ikonomou, M. G., Blair, J. D., Morin, A. E., and Gobas, F. 2007. Food web–specific biomagnification of persistent organic pollutants. *Science* **317:** 236–239.

Keyzr, M. A., Merbis, M. D., Pavel, I.F.P.W., and van Wesenbeeck C.F.A. 2005. Diet shifts towards meat and the effects on cereal use: Can we feed the animals in 2030? *Ecol.l Econ.* **55:** 187–202.

Khan, S., and Hanjra, M. A. 2009. Footprints of water and energy inputs in food production: Global perspectives. *Food Policy* **34:** 130–140.

Koplow, D., and Steenblik, R. 2008. Subsidies to ethanol in the Unites States. **In**: *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks*. pp. 79–108. Pimentel, D. Ed, Springer, New York.

Kristiansen, P., Taji, A., and Reganold, J. (Eds.) 2006. *Organic Agriculture. A Global Perspective*. CSIRO Publishing, Collingwood, Australia.

Kropff, M. J., Bouma, J., and Jones, J. W. 2001. Systems approaches for the design of sustainable agro-ecosystems. *Agric. Sys.* **70:** 369–393.

Lal, R. 2004. Soil carbon sequestration impact on global climate and food security. *Science* **304:** 1623–1627.

Lal, R. 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. *Soil & Tillage Res.* **93:** 1–12.

Lal, R. 2010. Enhancing eco-efficiency in agro-ecosystems through soil carbon sequestration. *Crop Sci.* 50: 120–131.

Lavelle, P., and Spain, A. V. 2002. *Soil Ecology*. Kluwer Academic Publishers, Amsterdam.

Liebert, B. 1995. *The Environmental Heritage of Soviet Agriculture*. CABI, Oxon, UK.

Lipsitch, M., Singer, R. S., and Levin, B. R. 2002. Antibiotics in agriculture: When is it time to close the barn door? *PNAS* **99:** 5752–5754.

Lockeretz, W. (Ed.) 2007. *Organic Farming: An International History*. CABI, Cambridge, MA.

López-Ridaura, S., Masera, O. and Aster, M. 2002. Evaluating the sustainability of complex socio-environmental systems the MESMIS framework. *Ecological Indicators* **35:** 1–14.

Lotter, D. W. 2003. Organic agriculture. *J. Sust. Agric.* **21:** 59–128.

Lowrance, R., Hendrix, P. F., and Odum, E. P. 1986. A hierarchical approach to sustainable agriculture. *Am. J. Alternative Agriculture* **1:** 169–173.

Lyons, G., 2009. Effects of pollutants on the reproductive health of male vertebrate wildlife - Males under threat. CHEM Trust (Chemicals, Health and Environment Monitoring) http://www.chemtrust.org.uk/documents/Male%20Wildlife%20Under%20Threat%202008%20full%20report.pdf Accessed on 10 May 2010.

Lu, C., Toepel, K., Irish, R., Fenske, R. A., Barr, D. B., and Bravo, R. 2006. Organic diets significantly lower children's dietary exposure to organophosphorus pesticides. *Environ. Health Perspectives* **114:** 260–263.

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. *Science* **296:** 1694–1697.

Matson, P. A., Parton, W. J., Power, A. G., and Swift, M. J. 1997. Agricultural intensification and ecosystem properties. *Science* **277:** 504–509.

McConnell, D. J., and Dillon, J. L. 1997. *Farm Management for Asia: A System Approach*. FAO Farm Systems Management Series – 13. FAO, Rome. http://www.fao.org/docrep/w7365e/w7365e00.HTM Accessed on 20 May 2010.

Millennium Ecosystem Assessment. 2005. *Millennium Ecosystem Assessment.* http://www.millenniumassessment.org/ Accessed 25 November 2009.

Molden, D. (Ed.). 2007. *Water for Food, Water for Life*. *A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London. Available at http://www.iwmi.cgiar.org/assessment/Publications/books.htm

Montgomery, D. R. 2007. *Dirt: The Erosion of Civilization*. University of California Press, Berkeley.

Moore, A. D., Holzworth, D. P., Herrmann, N. I., Huth, N. I., and Robertson, M. J. 2007. The Common Modelling Protocol: A hierarchical framework for simulation of agricultural and environmental systems. *Agric.l Syst.* **95:** 37–48.

Morris, C., and Winter, M. 1999. Integrated farming systems: The third way for European agriculture? *Land Use Policy* **16:** 193–205

Moss, B. 2008. Water pollution by agriculture. *Phil. Trans. B* **363:** 659–666.

Müller, P. H. 1948. Dichloro-diphenyl-trichloroethane and newer insecticides. Nobel Lecture, December 11, 1948 http://nobelprize.org/nobel_prizes/medicine/laureates/1948/muller-lecture.pdf Accessed on 20 May 2010.

Murphy, D. J. 2007. *Plant Breeding and Biotechnology: Societal Context and the Future of Agriculture*. Cambridge University Press, Cambridge.

Nandula, V. K. (Ed.) 2010. *Glyphosate Resistance in Crops and Weeds: History, Development, and Management*. Wiley, New York.

Naylor, R., Steinfeld, H., Falcon, W., Galloway, J., Smil, V., Bradford, E., Alder, J., and Mooney, M. 2005. Losing the links between livestock and land. *Science* **310:** 1621–162.

Niggli, U., Fließbach, A., Hepperly, P. and Scialabba, N. 2009. *Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems*. FAO, April 2009, Rev. 2 – 2009. ftp://ftp.fao.org/docrep/fao/010/ai781e/ai781e00.pdf Accessed on 20 May 2010.

Nord, M., Andrews, M., and Carlson, S. 2009. *Household Food Security in the United States, 2004*. US Department of Agriculture. http://www.ers.usda.gov/features/householdfoodsecurity/ accessed on 20 June 2010.

NRC (National Research Council). 2010. *Toward Sustainable Agricultural Systems in the 21st Century.* National Academies Press. http://www.nap.edu/catalog/12832.html Accessed on 20 March 2010.

Ochatt, S., and Jain, S. M. 2007. *Breeding of Neglected and Under-Utilized Crops Spices and Herbs*. Science Publisher, Enfield, New Hampshire, USA.

Odum, E. P. 1993. *Ecology and Our Endangered Life-Support Systems*. Sinauer Publishers, Sunderland, Mass.

Paoletti, M. G. (Ed.) 2005. *Ecological Implications of Minilivestock. Insects, Rodents, Frogs and Snails*. Science Publiscers Inc., Enfield, New Hampshire, USA.

Paoletti, M. G., and Bressan, M. 1996. Soil invertebrates as bioindicators of human disturbance. *Crit. Rev. Plant Sci*. **15:** 21–62.

Paoletti, M. G., and Bukkens, S.G.F. 1997. Minilivestock. *Ecology of Food and Nutrition*. **36:** Special Issue.

Paoletti, M. G., Pimentel, D., Stinner, B. R., and Stinner, D. 1992. Agroecosystem biodiversity: Matching production and conservation biology. *Agric. Ecosys. & Environ.* **40:** 3–26.

Paoletti, M. G., Stinner, B. R., and Lorenzoni, G. G. (Eds.) 1989. *Agricultural Ecology and Environment*. Elsevier Science Publishers, Amsterdam.

Paoletti, M. G., Thomson, L. J., and Hoffmann, A. A. 2007b. Using invertebrate bioindicators to assess agricultural sustainability in Australia: proposals and current practices. *J. of Australian Agric.* **47:** 379–478

Paoletti M. G., Tsitsilas A., Thomson L. J., Taiti S., and Umina, P. A. 2007a. The flood bug, *Australiodillo bifrons* (*Isopoda: Armadillidae*): A potential pest of cereals in Australia? *Appl. Soil Ecol.* **39:** 76–83.

Pardey, P. J., Alston, J. M., and Piggott, R. R. (Eds.) 2006. *Agricultural R&D in the Developing World: Too Little, TooLate?* International Food Policy Research Institute, Washington, DC. http://www.ifpri.org/sites/default/files/publications/oc51.pdf Accessed 20 February 2010.

Park, J., and Seaton, R.A.F. 1996. Integrative research and sustainable agriculture. *Agricultural Systems* **50:** 81–100.

Pesticide News. 2001. Persistence pays – lower risks from pesticides in Sweden. Pesticide News No. 54, pp. 10–11. http://www.pan-uk.org/pestnews/Issue/pn54/pn54p10.htm Accessed on 11 February 2010.

PHLIS (Post Harvest Losses Information System). 2010. http://www.phlosses.net/index.php?form=home, Accessed 20 May 2010.

Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudre, N., Labat, D., and Zaehle, S. 2007. Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. *PNAS* **104:** 15242–15247.

Pimentel, D. 2010. *The Effects of the Resistance of Antibiotics and Pesticides on U.S. Public Health.* Institute of Medicine, National Academy of Sciences, Washington, D.C. (In Press)

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E., and Nandagopal, S. 2004. Water resources: Agricultural and environmental issues. *BioScience* **54:** 909–918.

Pimentel, D., and Cilveti, M. V. 2007. Reducing pesticide use: Successes. **In**: *Encyclopedia of Pest Management.* Volume 2. pp. 551–552. Pimentel, D. Ed, Taylor & Francis, Boca Raton, Fl, USA.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., and Seidel, R. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. *Bioscience* **55:** 573–582.

Pimentel, D., and Kounang, N. 1998. Ecology of soil erosion in ecosystems. *Ecosystems* **1:** 416–426.

Pimentel, D., Marklein, A., Toth, M. A., Karpoff, M., Paul, G. S., McCormack, R., Kyriazis, J., and Krueger, T. 2009. Food versus biofuels: Environmental and economic costs. *Human Ecology* **37:** 1–12.

Pimentel, D., Petrovna, T., Riley, M., Jacquet, J., Ng, V., Honigman, J., and Valero, E. 2006. Conservation of Biological Diversity in Agricultural, Forestry, and Marine Systems. **In**: *Focus on Ecology Research*. pp. 151–173. Nova Science Publishers, New York, (Also, 2007. **In**: *Focus on Biodiversity Research*. pp. 1–25. Nova Science Publishers, New York)

Pimentel, D., and Pimentel, M. 2008. *Food, Energy, and Society. 3^d* ed. CRC Press, Boca Raton, FL.

Pimentel, D., and Satkiewicz, P. 2010. Malnutrition. *Environmental Ethics*. (In Press)

Piorr, H.-P. 2003. Environmental policy, agri-environmental indicators and landscape indicators. *Agric. Ecosyst. & Environ.* **98:** 17–33.

Postel, S. L. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* W.W. Norton, New York.

PRB (Population Reference Bureau). 2009. 2009 *World Population Data Sheet*. Population Reference Bureau, Washington, D.C. http://www.prb.org/publications/datasheets/2009/2009wpds.aspx Accessed on 2 July 2010.

Pretty, J. 2002. *Agri-Culture: Reconnecting People, Land and Nature.* Earthscan, London.

Pretty, J. (Ed.). 2005. *The Pesticide Detox*. Earthscan, London.

Pretty, J. 2008. Agricultural sustainability: Concepts, principles and evidence. *Phil. Trans. B* **363:** 447–465.

Qiu, J. 2010. GM crop use makes minor pests major problem. *Nature* http://www.nature.com/news/2010/100513/full/news.2010.242.html

Quinton, J. N., Govers, G., Van Oost, C., and Bardgett, R. D. 2010. The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience* **3:** 311–314.

Rasmussen, P. E., Goulding, K. W. T., Brown, J. R., Grace, P. R., Janzen, H. H., and Körschens, M. 1998. Long-term agroecosystem experiments: Assessing agricultural sustainability and global change. *Science* **282:** 893–896.

Reganold, J., Elliott, L., and Unger, Y. 1987. Long-term effects of organic and conventional farming on soil erosion. *Nature* **330:** 370–372.

Richter, E. D. 2002. Acute human pesticide poisonings. **In:** *Encyclopedia of Pest Management*. pp. 3–6. Pimentel, D. Ed., Taylor & Francis, Boca Raton, Fl, USA.

Rifkin, J. 1992. *Beyond Beef: The Rise and Fall of the Cattle Culture*. Dutton Books, Boston, MA.

Renault, D. 2002. *Value of Virtual Water in Food: Principles and Virtues*. FAO, Rome. http://www.fao.org/nr/water/docs/VirtualWater.pdf Accessed on 16 November 2009.

Rockstrom, J., Lannerstad, M., and Falkenmark, M. 2007. Assessing the water challenge of a new green revolution in developing countries. *PNAS* **104:** 6253–6260.

Rojstaczer, S., Sterling, S. M., and Moore, N. J. 2001. Human appropriation of photosynthesis products. *Science* **294:** 2549–2552.

Romeis, J., Bartsch, D., Bigler, F., Candolfi, M. P., et al. 2008. Assessment of risk of insect-resistant transgenic crops to nontarget arthropods. *Nature Biotechnology* **26:** 203–208.

Rosegrant, M. W., Leach, N., and Gerpacio, R. V. 1999. Alternative futures for world cereal and meat consumption. *Proceed. Nutrition Society* **58:** 219–234.

Rotmans, J., and van Asselt, M.B.A. 1996. Integrated assessment: Growing child on its way to maturity. An editorial essay. *Climatic Change* **34:** 327–336.

Royal Society of London. 2009. *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*. RS Policy document 11/09 Issued: October 2009 RS1608, London. http://royalsociety.org/Reapingthebenefits/ Accessed on 23 March 2009.

Russell, E. W. 1977. The role of organic matter in soil fertility. *Phil. Trans. B* **281:** 209–219.

Ruttan, V. W. 1999. The transition to agricultural sustainability. *PNAS* **96:** 5960–5967.

Sachs, J. D., Baillie, J.E.M., Sutherland, W. J., et al. 2009. Biodiversity Conservation and the Millennium Development Goals. *Science* **325:** 1502–1503.

Service, R. F. 2007. A growing threat down on the farm. *Science* **316:** 1114–1117.

Smil, V. 1991. Population growth and nitrogen: An exploration of a critical existential link. *Population and Development Review* **17:** 569–601.

Smil, V. 2000. *Feeding the World: A Challenge for the Twenty-first Century.* The MIT Press, Cambridge, MA.

Smil, V. 2002. Eating meat: Evolution, patterns, and consequences. *Population and Develop. Rev.* **28:** 599–639.

Smil, V. 2004. *Enriching the Earth. Fritz Haber, Carl Bosch, and the Transformation of World Food Production.* The MIT Press, Cambridge, MA.

Smil, V. 2008. Water news: Bad, good and virtual. *American Scientist* **96:** 339–407.

Smith, D. K., Dushoff, J., and Morris, G. Jr. 2005. Does antibiotic use in agriculture have a greater impact than hospital use? *PLoS Medicine* **2:** e232. http://medicine.plosjournals.org/perlserv/?request=get-document&doi=10.1371/journal.pmed.0020232 Accessed on 20 March 2010.

Sommaggio, D., Paoletti, M. G. and Ragusa, S. 1995. Effects of microhabitat conditions, nutrients and predators on the abundance of herbivores on stinging nettles (*Urtica dioica* L.). *Acta Oecologica* **16:** 671–686.

Stokstad, E. 2008. Duelling visions for a hungry world. *Science* **319:** 1474–1476.

Stokstad, E. 2010. Could less meat mean more food? *Science* **327:** 810.811.

Stone, G. D. 2002. Fallacies in the genetic-modification wars, implication for developing countries, an anthropological perspective. *Current Anthropology* **43:** 611–630.

Stuart, T. 2009. *Waste: Uncovering the Global Food Scandal*. Penguin Books, London.

Sydorovych, O., and Wossink, A. 2008. The meaning of agricultural sustainability: Evidence from a conjoint choice survey. *Agricultural Systems* **98:** 10–20.

Tabashnik, B. E., Gassmann, A.J ., Crowder, D. W., and Carrière, Y. 2008. Insect resistance to *Bt* crops: evidence versus theory. *Nature Biotechnology* **26:** 199–2002.

Tabashnik, B., Unnithan, G. C., Masson, L., Crowder, D. W., Li, X., and Carriere, Y. 2009. Asymmerical cross-resistance between Bt toxins Cry 1Ac and Cry2Ab in pink bollworm. *PNAS* **106:** 11889–11894.

Tester, M., and Langridge, P. 2010. Breeding technologies to increase crop production in a changing world. *Science* **327:** 818–822.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. 2002. Agricultural sustainability and intensive production practices. *Nature* **418:** 671–677.

Trewavas, A. J. 2001. The population/biodiversity paradox. Agricultural efficiency to save wilderness. *Plant Physiology* **125:** 174–179.

USGOA (United States Government Accountability Office). 2007. Biofuels: DOE lacks a strategic approach to coordinate increasing production with infrastructure development and vehicle needs. http://www.gao.gov/new.items/d07713.pdf Accessed on 15 August 2010.

Vaderevu, P. K., Cardina, J., Hitzhusen, F., Bayoh, I., Moore, R., Parker, J., Stinner, B., Stinner, D., and Hoy, C. 2008. Case study of an integrated framework for quantifying agroecosystem health. *Ecosystems***11:** 283–306.

van Cauwenbergh, N., Biala, K., Bielders, C., Brouckaert, V., Franchois, L., Cidad, V. G., et al. 2007. SAFE – a hierarchical framework for assessing the sustainability of agricultural systems. *Agric. Ecosyst. & Environ.* **120:** 229–242.

van den Bergh, J.C.J.M., and Verbruggen, H. 1999. Spatial sustainability, trade and indicators: an evaluation of the “ecological footprint.” *Ecological Economics* **29:** 61–72.

van Ittersum, M.K., Ewert, F., Heckeiei, T., Nery, J., Alkan Olsson, J., et al. 2008. Integrated assessment of agricultural systems – A component-based framework for the European Union (SEAMLESS). *Agricultural Systems* **96:** 150–165.

Vaquero, F., and Blázquez, J. 1997. Evolution of antibiotic resistance. *TREE* **12:** 482–487.

Verburg, P. H., Rounsevell, M.D.A., and Veldkamp, A. 2006. Scenario-based studies of future land use in Europe. *Agric. Ecosyst. & Environ.* **114:** 1–6.

Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H., and Matson, P. A. 1986. Human Appropriation of the Products of Photosynthesis. *BioScience* **36:** 363–373.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M. 1997. Human domination of earth's ecosystems. *Science* **277:** 494–499.

Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E., Johnes, P. J., et al. 2009. Nutrient imbalances in agricultural development. *Science* **324:** 1519–1520.

von Wirén-Lehr, S. 2001. Sustainability in agriculture - an evaluation of principal goal oriented concepts to close the gap between theory and practice. *Agric. Ecosyst. & Environ.* **84:** 115–129.

VV. AA. 2009. Managing stink bugs in cotton: Research in the Southeast region. Virginia Cooperative Extension. http://pubs.ext.vt.edu/444/444-390/444-390.pdf Accessed on 20 May 2010.

Wackernagel, M., and Rees, W. 1996. *Our Ecological Footprint: Reducing Human Impact on the Earth*., New Society Publishers, Gabriola Island, BC.

Wackernagel, M., Schulz, N. B., Deumling, A. C., Linares, A. C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., and Randers, J. 2002. Tracking the ecological overshoot of the human economy. *PNAS* **99:** 9266–9271.

Waltz, E. 2009. GM crops: Battlefield. *Nature* **461:** 27–32.

Wardle, D. A., Bardgett, R. D., Klironomos, J. N., Setälä, H., van der Putten, W. H., and Wall, D. H. 2004. Ecological linkages between aboveground and belowground biota. *Science* **304:** 1629–1633.

Wilkins, R. J. 2008. Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. *Phil. Trans. B* **363:** 517–525.

WHO. 2000. Nutrition for health and development: A global agenda for combating malnutrition. World Health Organization, Nutrition for Health and Development (NHD), Sustainable Development and Healthy Environments (SDE). Accessed July 21, 2010. http://whqlibdoc.who.int/hq/2000/WHO_NHD_00.6.pdf

WHO (World Health Organization). 2005. Obesity and overweight. http://www.who.int/mediacentre/factsheets/fs311/en/index.html

WHO/FAO, 2004. Childhood pesticide poisoning. Information for advocacy and action. Ginevra. http://www.who.int/ceh/publications/pestpoisoning.pdf Accessed on 20 March 2010.

Wolfenbarger, L. L., and Phifer, P. R. 2000. The ecological risks and benefits of genetically engineered plants. *Science* **290:** 2088–2093.

World Bank. 2008. *World Development Report 2008: Agriculture for Development*. World Bank, Washington, DC. http://siteresources.worldbank.org/INTWDR2008/Resources/WDR_00_book.pdf Accessed 27 October 2009.

Critical Reviews in Plant Sciences, 30:24–34, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.553539

Resources and Cultural Complexity: Implications for Sustainability

Joseph A. Tainter
Department of Environment and Society, Utah State University, Logan, Utah 84322, USA

Table of Contents

In the cosmology of Western industrial societies, "progress" results from human creativity enacted in facilitating circumstances. In human history, creativity leading to progress was supposedly enabled by the development of agriculture, which provided surplus energy and freed people from needing to spend full time in subsistence pursuits. Applying this belief to the matter of sustainability today leads to the supposition that we can voluntarily reduce resource use by choosing a simpler way of life with lower consumption. Recent research suggests that these beliefs are deeply inaccurate. Humans develop complex behaviors and institutions to solve problems. Complexity and problem solving carry costs and require resources. Rather than emerging from surplus energy, cultural complexity often precedes the availability of energy and compels increases in its production. This suggests that, with major problems converging in coming decades, voluntary reductions in resource consumption may not be feasible. Future sustainability will require continued high levels of energy consumption.

Keywords collapse, complexity, cultural evolution, resources, sustainability

---

Address correspondence to Joseph A. Tainter, Department of Environment and Society, Utah State University, Logan, Utah 84322, USA. E-mail: Joseph.Tainter@usu.edu

Referee: Prof. T. F. H. Allen, Department of Botany, University of Wisconsin, 430 Lincoln Drive, Madison, WI 53706, USA.

I. RESOURCES AND CULTURAL COMPLEXITY

Few questions of the social sciences have been more enduring than how today's complex societies evolved from the small foraging bands of our ancestors. While this question might seem to be of narrow academic interest, it has in fact implications of the highest importance for anticipating our future. Our understanding of sustainability and the human future depends to a surprising degree on our understanding of the human past. The emphasis of this essay is to show that some of the conventional understandings of cultural evolution are untenable, as are assumptions about sustainability that follow from them. A new framework is presented that will more realistically delineate the future connection of resources to sustainability.

Complexity is a popular topic today, and there are various conceptions of it. One can find, in various literatures, references to physical complexity, ecological complexity, algorithmic complexity, computational complexity, social complexity, and probably other varieties as well. Complexity can be specified, irreducible, or unruly. Complexity can occur within a system, or by embedding different levels of systems. The concept used here derives from Anthropology, and specifically from this discipline's focus on the ancestry of today's complex society.

The focus is cultural complexity, encompassing all of the social, ideological, behavioral, economic, and technological elements that comprise a cultural system. Cultural complexity consists of differentiation in structure and variation in organization. As human societies have evolved they have developed more differentiated structures. Julian Steward, for example, once noted the difference between the 3,000 to 6,000 cultural elements early anthropologists documented for native populations of western North America, and the more than 500,000 artifact types that U.S. military forces landed at Casablanca in World War II (1955). Similarly, hunter-gatherer societies incorporate no more than a few dozen distinct social personalities, while modern European censuses recognize 10,000 to 20,000 unique occupational roles, and industrial societies may contain overall more than 1,000,000 different kinds of social personalities (McGuire, 1983).

But structural differentiation alone does not equal complexity. The behavior of structural elements (such as roles and institutions) must be constrained for the elements to function as a system. This constraint is provided through organization. Organization limits and channels behavior, making the activities of behavioral elements predictable. Organization gives a system coherence. For example, although the materiél that U.S. forces took to Casablanca was highly differentiated (500,000 artifact-types, as noted by Steward), it was not fully a complex system. The materiél was loaded on the transport ships in a haphazard fashion (Atkinson, 2002). The results were predictable. As Atkinson describes, "Guns arrived on the beach with no gunsights; guns arrived with no ammunition; guns arrived with no gunners" (2002). About 260,000 tons of materiél, enough for 1.5 months of fighting, simply disappeared in Britain. There was a clear lack of organization, which is what differentiated structures require to form a system. Without organization (normally provided by "combat loading"), the impressive lot of materiél was merely an assemblage. In human history, complex societies evolved through increasingly differentiated structures that were integrated by increasing organization.

Cultural complexity is deeply embedded in our contemporary self-image, although colloquially we do not know it by that term. Rather, cultural complexity is known in popular discourse by the more common term "civilization," which we believe our ancestors achieved through the phenomenon called "progress." The concepts of civilization and progress have a status in the cosmology of industrial societies that amounts to what anthropologists call "ancestor myths." Ancestor myths validate a contemporary social order by presenting it as a natural and sometimes heroic progression from earlier times. Just as Pueblo Indians tell how their ancestors emerged from the underworld and California Indians tell how the trickster Coyote changed the world, so in industrial societies we tell how our ancestors discovered fire, agriculture, and the wheel, and conquered untamed continents.

Social scientists label this a "progressivist" view of cultural evolution. It is based on the supposition that cultural complexity is intentional, that it emerged merely through the inventiveness of our ancestors, the outcome constituting progress. Progressivism is the dominant ideology of free-market societies today. But inventiveness is not a sufficient explanation for cultural complexity. It is not a constant in human history. Rather, inventiveness must be enacted in facilitating circumstances. What were those circumstances? Prehistorians once thought they had the answer: The discovery of agriculture gave our ancestors surplus food and, comcomitantly, free time to invent urbanism and the things that comprise "civilization" (e.g., Childe, 1944). Through the mechanism of agriculture, plants figure centrally in the progressivist view of cultural evolution. Vere Gordon Childe may be the prehistorian most influential in propagating this argument. He wrote:

> On the basis of the neolithic economy further advances could be made...in that farmers produced more than was needed for domestic consumption to support new classes...in secondary industry, trade, administration or the worship of gods (1944).

Eventually, in this line of reasoning, progress facilitated by agricultural surpluses led to the emergence of cities, artisans, priesthoods, kings, aristocracies, and all of the other features of what are called archaic states (Childe, 1944).

At first glance Childe's argument appears plausible. Its seeming reasonableness, though, stems from its logical consistency with the progressivist ideology of industrial societies. Give humans the resources to invent cultural complexity and axiomatically, it is believed, they will. Prehistorians, after all, are themselves socialized members of industrial societies. They are raised to believe the values and ideologies of their societies, so it is natural that they internalize a progressivist view. This unsurprisingly influences their interpretations of the past. Archaeology emerged as a pastime of the middle and upper classes, and early frameworks for arranging the past—ages of stone, bronze, and iron, for example—reflect a belief in material progress. Consider the implied progressivism of the titles of some prominent books:

- *Man Makes Himself* (Childe, 1951),
- *Man's Rise to Civilization: The Cultural Ascent of the Indians of North America* (Farb, 1978),
- *The Ascent of Man* (Bronowski, 1973).

While these are older works, the progressivist view persists to this day. It is exemplified prominently in the recent popular books of Jared Diamond (1997, 2005; see Tainter, 2005).

II. CHALLENGING THE PROGRESSIVIST VIEW

The progressivist view posits a specific relationship between resources (including plants) and civilization. It is that complexity emerges because it can, and that the factor facilitating this is surplus energy arising from such innovations as fire, agriculture, and the wheel. Surplus energy precedes complexity and allows it to emerge. Unfortunately for popular cosmology there are significant reasons to doubt the extent to which surplus energy has driven cultural evolution.

One strand of thought that challenges progressivism emerged in the eighteenth century with the works of Wallace (1761) and Malthus (1798). Malthus was influenced by Wallace, who argued that progress would undermine itself by filling the world with people. Stimulated by Malthus, Jevons (1866) worried that Britain's industrial development and global leadership would outrun the supply of coal. Jevons argued that as technological improvements increase the efficiency with which a resource is used, total consumption of that resource may increase rather than decrease. This became known as the Jevons Paradox or Rebound Effect (Polimeni *et al*., 2008). Malthus also set the stage for contemporary theorists of consumption overshoot, such as Erlich (1968) and Catton (1980).

Boulding derived from Malthus's essay on population three theorems. The first is called the Dismal Theorem:

> If the only ultimate check on the growth of population is misery, then the population will grow until it is miserable enough to stop its growth (Boulding, 1959).

Theorem two is the Utterly Dismal Theorem, and it directly challenges the progressivist view:

> Any technical *improvement* can only relieve misery for a while, for as long as misery is the only check on population, the improvement will enable population to grow, and will soon enable *more* people to live in misery than before. The final result of improvements, therefore, is to increase the equilibrium population, which is to increase the sum total of human misery (Boulding, 1959 [emphases in original]).

Boulding's third theorem is called the moderately cheerful form of the Dismal Theorem:

> If something else, other than misery and starvation, can be found which will keep a prosperous population in check, the population does not have to grow until it is miserable and starves, and can be stably prosperous (Boulding, 1959).

Boulding observed that how to implement the Cheerful Theorem "is a problem which has so far produced no wholly satisfactory solution" (1959).

The implication of this strain of thought is that humans have rarely had surplus energy. When we have had surplus resources, we have not had them regularly or in abundance for long. Surpluses have been dissipated quickly by growth in consumption. Since humans have rarely had surpluses, the availability of energy cannot be the primary driver of cultural evolution.

Beyond a Malthusian view, there is another strand of criticism that undermines progressivism. It is that complexity costs. In any living system, increased complexity carries a metabolic cost. In non-human species this cost is a straightforward matter of additional calories that must be found and consumed. Among humans the cost is calculated in such currencies as resources, effort, time, or money, or by more subtle matters such as annoyance. While humans find complexity appealing in spheres such as art, music, or architecture, we usually prefer that someone else pay the cost. We are averse to complexity when it unalterably increases the cost of daily life without a clear benefit to the individual or household. Before the development of fossil fuels, increasing the complexity and costliness of a society meant that *people* worked harder.

The development of complexity is thus a paradox of human history. Over the past 12,000 years, we have developed technologies, economies, and social institutions that cost more labor, time, money, energy, and annoyance, and that go against our aversion to such costs. We have progressively adopted ways of life that impose increasing costs on both societies and individuals, and that contravene some of our deepest inclinations. Why, then, did human societies ever become more complex?

At least part of the answer is that complexity is a basic problem-solving tool. Confronted with problems, we often respond by developing more complex technologies, establishing new institutions, adding more specialists or bureaucratic levels to an institution, increasing organization or regulation, or gathering and processing more information. Such increases in complexity work in part because they can be implemented rapidly, and typically build on what was developed before. While we usually prefer not to bear the cost of complexity, our problem-solving efforts are powerful complexity generators. All that is needed for growth of complexity is a problem that requires it. Since problems continually arise, there is persistent pressure for complexity to increase (Tainter 1988, 1996, 2000, 2006).

Growth of complexity is well illustrated in the response to the attacks on the United States of September 11, 2001. In the aftermath, steps taken to prevent future similar attacks focused on creating new government agencies, such as the Transportation Security Administration and the Department of Homeland Security, consolidating existing functions into some of the new agencies, and increasing control over realms of behavior from which a threat might arise. In other words, our first response was to complexify—to diversify structure and function, and to increase organization or control. The report of the government commission convened to investigate the attacks (colloquially called the 9/11 Commission) recommended steps to prevent future attacks. The recommended actions amount, in effect, to more complexity, requiring more costs in the form of resources, time, or annoyance (9/11 Commission, 2004).

The costliness of complexity is not a mere annoyance or inconvenience. It conditions the long-term success or failure of problem-solving efforts. Complexity can be viewed as an economic function. Societies and institutions invest in problem solving, undertaking costs and expecting benefits in return. In any system of problem solving, early efforts tend to be simple and cost-effective. That is, they work and give high returns per unit of effort. This is a normal economic process: humans always tend to pluck the lowest fruit, going to higher branches only when those lower no longer hold fruit. In problem-solving systems, inexpensive solutions are adopted before more complex and expensive ones. In the history of human food-gathering

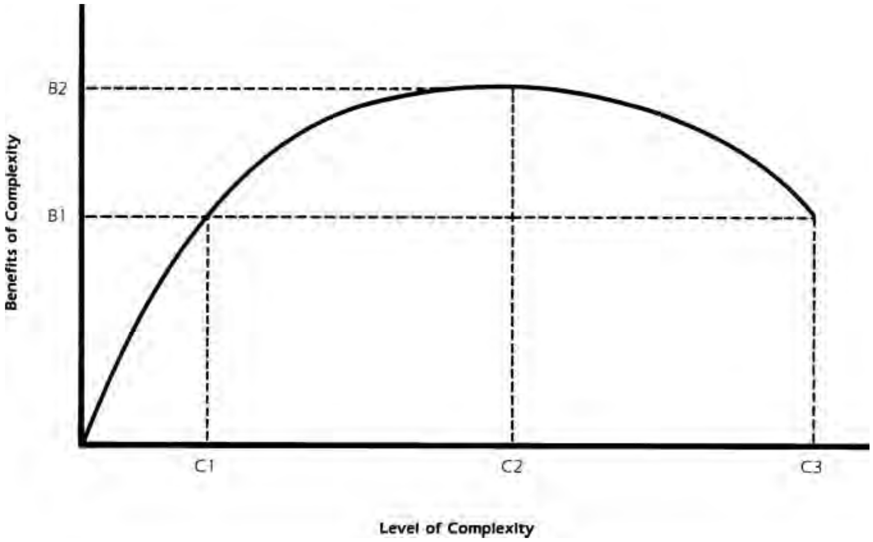

FIG. 1. The marginal productivity of increasing complexity. At a point such as B1, C3, the costs of complexity exceed the benefits, and complexity is a disadvantageous approach to problem solving.

and production, for example, labor-sparing hunting and gathering gave way to more labor-intensive agriculture, which in some places has been replaced by industrial agriculture that consumes more energy than it produces (Boserup, 1965; Clark and Haswell, 1966; Cohen, 1977). We produce minerals and energy whenever possible from the most economic sources. Our societies have changed from egalitarian relations, economic reciprocity, *ad hoc* leadership, and generalized roles to social and economic differentiation, specialization, inequality, and full-time leadership. These characteristics are the essence of complexity, and they increase the costliness of any society.

As high-return solutions are progressively implemented, only more costly solutions remain. As the highest-return ways to produce resources, process information, and organize society are applied, continuing problems must be addressed in ways that are more costly and less cost-effective. As the costs of solving problems grow, the point is reached where further investments in complexity do not give a proportionate return. Increments of investment in complexity begin to yield smaller and smaller increments of return. The *marginal* return (that is, the return per extra unit of investment) starts to decline (Figure 1).

This is the long-term challenge faced by problem-solving institutions: diminishing returns to complexity. If allowed to proceed unchecked, eventually it brings ineffective problem solving and even economic stagnation. A prolonged period of diminishing returns to complexity is a major part of what makes problem solving ineffective and societies or institutions unsustainable (Tainter, 1988, 1999, 2000, 2006).

In the progressivist view, surplus energy precedes and facilitates the evolution of complexity. Certainly this is sometimes true: There have been occasions when humans adopted energy sources of such great potential that, with further development and positive feedback, there followed great expansions in the numbers of humans and the wealth and complexity of societies. These occasions have, however, been rare, so much so that we designate them with terms signifying a new era: the Agricultural Revolution and the Industrial Revolution (which depended on fossil fuels). It is worth noting that these unusual transitions have not resulted from unbridled human creativity. Rather, they emerged from solutions to problems of resource shortages, and were adopted reluctantly because initially they created diminishing returns on effort in peoples' daily lives (Cohen, 1977; Wilkinson, 1973).

Most of the time, cultural complexity increases in a purely mundane manner: from day-to-day exercises in solving problems. Most importantly for this essay, complexity that emerges in this way will usually appear *before* there is additional energy to support it. Complexity thus compels increases in resource production. Rather than following the availability of energy, cultural complexity often precedes it. Energy lags complexity rather than the reverse. This new understanding of the temporal relationship between complexity and resources has implications for sustainability that diverge from what is commonly assumed. These implications will be explored at the end of this essay. It is useful first to present historical case studies that illustrate the points made in this section.

III. CASE STUDIES IN ENERGY AND COMPLEXITY

I describe next two historical cases that illustrate the relationship of resources to problem solving and complexity. These are the collapse of the Western Roman Empire in the fifth century A.D. and the collapse of the Byzantine Empire in the seventh century A.D., followed by Byzantine recovery. These cases are chosen for the lessons they impart about sustainability today.

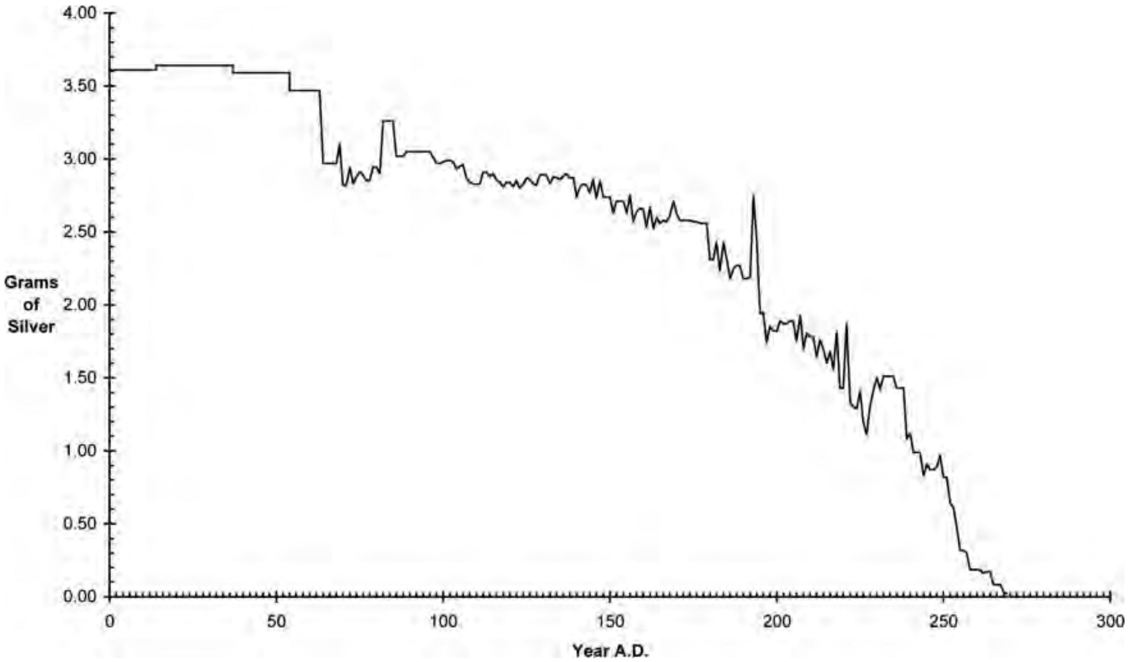

FIG. 2. Debasement of the denarius to 269 A.D. Source: Tainter (1994).

A. Collapse of the Western Roman Empire

The economics of an empire such as the Romans assembled are seductive but illusory. The returns to any campaign of conquest are highest initially, when the accumulated surpluses of the conquered peoples are appropriated. Thereafter the conqueror assumes the cost of administering and defending the province. These responsibilities may last centuries, and are paid for from yearly agricultural surpluses.

The Roman government was financed by agricultural taxes that barely sufficed for ordinary administration. When extraordinary expenses arose, typically during wars, the precious metals on hand frequently were insufficient. Facing the costs of war with Parthia and rebuilding Rome after the Great Fire, Nero began in 64 A.D. a policy that later emperors found irresistible. He debased the primary silver coin, the denarius, reducing the alloy from 98 to 93 percent silver. It was the first step down a slope that resulted two centuries later in a currency that was worthless and a government that was insolvent (Figure 2).

In the half-century from 235 to 284 the empire nearly came to an end. There were foreign and civil wars almost without interruption. The period witnessed 26 legitimate emperors and perhaps 50 usurpers. Cities were sacked and frontier provinces devastated. The empire shrank in the 260s to Italy, the Balkans, and North Africa. By prodigious effort the empire survived the crisis, but it emerged at the turn of the fourth century A.D. as a very different organization.

In response to the crises, Diocletian and Constantine, in the late third and early fourth centuries, designed a government that was larger, more complex, and more highly organized. They doubled the size of the army. To pay for this the government taxed its citizens more heavily, conscripted their labor, and dictated their occupations. Villages were responsible for the taxes on their members, and one village could even be held liable for another. Despite several monetary reforms a stable currency could not be found (Figure 3).

As masses of worthless coins were produced, prices rose higher and higher. Money-changers in the east would not convert imperial currency, and the government refused to accept its own coins for taxes.

With the rise in taxes, population could not recover from plagues in the second and third centuries. There were chronic shortages of labor. Marginal lands went out of cultivation. Faced with taxes, peasants would abandon their lands and flee to the protection of a wealthy landowner. By 400 A.D. most of the lands of Gaul and Italy were owned by about 20 senatorial families.

From the late fourth century the peoples of central Europe could no longer be kept out. They forced their way into Roman lands in western Europe and North Africa. The government came to rely almost exclusively on troops from Germanic tribes. When finally they could not be paid, they overthrew the last emperor in Italy in 476 (Boak, 1955; Russell, 1958; Jones, 1964, 1974; Hodgett, 1972; MacMullen, 1976; Wickham, 1984; Williams, 1985; Tainter, 1988; 1994; Duncan-Jones, 1990; Harl, 1996).

The strategy of the later Roman Empire was to respond to a near-fatal challenge in the third century by increasing the size, complexity, power, and costliness of the primary problem-solving system—the government and its army. The higher costs were undertaken not to expand the empire or to acquire new

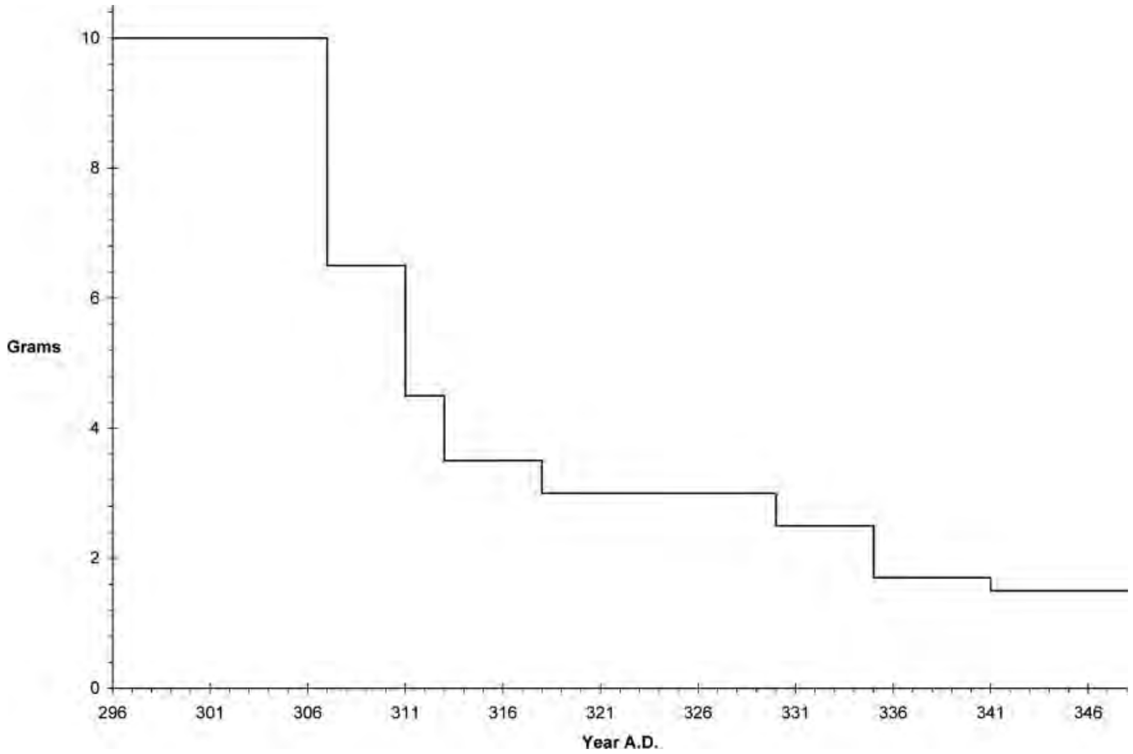

FIG. 3. Reductions in the weight of the follis, 296 to 348 A.D. (data from Van Meter, 1991).

wealth, but to maintain the status quo. The benefit/cost ratio of imperial government declined. In the end the Western Roman Empire could no longer afford the problem of its own existence (Tainter, 1988, 1994, 2000, 2006; Allen, Tainter, and Hoekstra, 2003; Tainter and Crumley, 2007).

B. Collapse and Recovery of the Byzantine Empire

The Eastern Roman Empire (usually known as the Byzantine Empire) survived the fifth century debâcle. Efforts to develop the economic base, and to improve the effectiveness of the army, were so successful that by the mid sixth century Justinian (527–565) could engage in a massive building program and attempt to recover the western provinces.

By 541 the Byzantines had conquered North Africa and most of Italy. Then that year bubonic plague swept over the Mediterranean for the first time. Just as in the fourteenth century, the plague of the sixth century killed from one-fourth to one-third of the population. The loss of taxpayers caused immediate financial and military problems. In the early seventh century the Slavs and Avars overran the Balkans. The Persians conquered Syria, Palestine, and Egypt. Constantinople was besieged for seven years.

The emperor Heraclius cut pay by half in 616, and proceeded to debase the currency (Figure 4).

These economic measures facilitated his military strategy. In 626 the siege of Constantinople was broken. The Byzantines destroyed the Persian army and occupied the Persian king's favorite residence. The Persians had no choice but to surrender all the territory they had seized. The Persian war lasted 26 years, and resulted only in restoration of the status quo of a generation earlier.

The empire was exhausted by the struggle. Arab forces, newly converted to Islam, defeated the Byzantine army decisively in 636. Syria, Palestine, and Egypt, the wealthiest provinces, were lost permanently. The Arabs raided Asia Minor nearly every year for two centuries, forcing thousands to hide in underground cities. Constantinople was besieged each year from 674 to 678. The Bulgars broke into the empire from the north. The Arabs took Carthage in 697. From 717 to 718 an Arab force besieged Constantinople continuously for over a year. It seemed that the empire could not survive. The city was saved in the summer of 718, when the Byzantines ambushed reinforcements sent through Asia Minor, but the empire was now merely a shadow of its former size.

Third- and fourth-century emperors had managed a similar crisis by increasing the complexity of administration, the regimentation of the population, and the size of the army. This was paid for by such levels of taxation that lands were abandoned and peasants could not replenish the population. Byzantine emperors could hardly impose more of the same exploitation on the depleted population of the shrunken empire. Instead they adopted a strategy that is truly rare in the history of complex societies: systematic simplification.

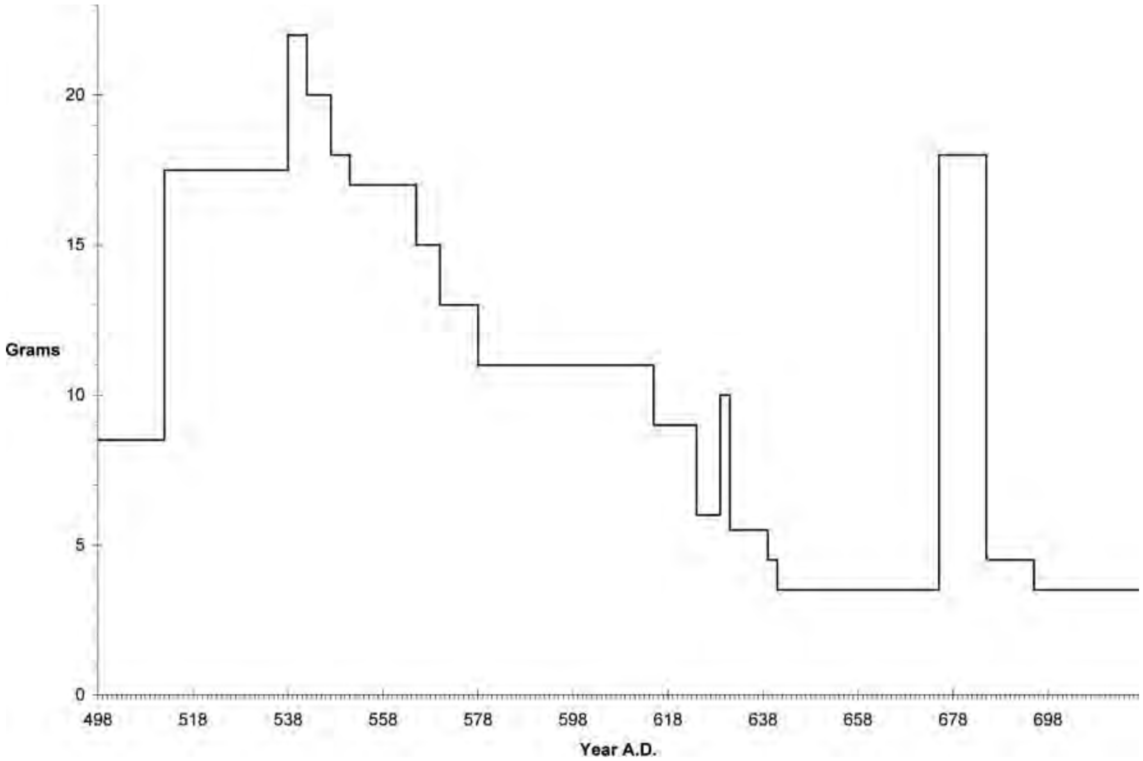

FIG. 4. Weight of the Byzantine follis, 498–717 A.D. (data from Harl, 1996).

Around 659 military pay was cut in half again. The government had lost so much revenue that even at one-fourth the previous rate it could not pay its troops. The solution was for the army to support itself. Soldiers were given grants of land on condition of hereditary military service. The Byzantine fiscal administration was correspondingly simplified.

The transformation ramified throughout Byzantine society. Both central and provincial government were simplified, and the costs of government were reduced. Provincial civil administration was merged into the military. Cities across Anatolia contracted to fortified hilltops. The economy developed into its medieval form, organized around self-sufficient manors. There was little education beyond basic literacy and numeracy, and literature itself consisted of little more than lives of saints. The period is sometimes called the Byzantine Dark Age.

The simplification rejuvenated Byzantium. The peasant-soldiers became producers rather than consumers of the empire's wealth. By lowering the cost of military defense the Byzantines secured a better return on their most important investment. Fighting as they were for their own lands and families, soldiers performed better.

During the next century, campaigns against the Bulgars and Slavs gradually extended the empire in the Balkans. Greece was recaptured. Pay was increased after 840, yet gold became so plentiful that in 867 Michael III met an army payroll by melting down 20,000 pounds of ornaments from the throne room. When marines were added to the imperial fleet it became more effective against Arab pirates. In the tenth century the Byzantines reconquered parts of coastal Syria. Overall after 840 the size of the empire was nearly doubled. The process culminated when Basil II (963–1025) conquered the Bulgars and extended the empire's boundaries again to the Danube (Treadgold, 1988, 1995, 1997; Haldon, 1990; Harl, 1996). In two centuries the Byzantines had gone from near disintegration to being the premier power in Europe and the Near East, an accomplishment won by decreasing the complexity and costliness of problem solving.

IV. DISCUSSION

The Roman and Byzantine case studies illustrate different outcomes to complexification, and offer different lessons for understanding sustainability. The Roman collapse exemplifies the thesis of this essay, that increasing complexity precedes the availability of energy and subsequently compels increases in its production. The Byzantine collapse and recovery illustrate a different but also important point, which will be discussed later.

The Roman Empire is a single case study in complexity and problem solving (for others, see Tainter, 1988, 2000, 2002, 2006; Allen *et al.*, 2003), but it is an important and representative one. It illustrates one of the basic processes by which societies increase in complexity. Societies adopt increasing complexity to solve problems, becoming at the same time more costly. In the normal course of economic evolution, this process at some point will produce diminishing returns. Once diminishing returns set in, a problem-solving institution must either find new resources to continue the activity, or fund the activity by reducing the share of resources available to other economic sectors. The latter is likely to produce economic contraction, popular discontent, and eventual collapse. This was the fate of the Western Roman Empire.

This understanding of complexity and resources has implications for our contemporary discussions of energy and sustainability. Both popular and academic discourse on sustainability commonly make the following assumptions: that (a) future sustainability requires that industrial societies consume a lower quantity of resources than is now the case (e.g., Brown, 2008; Caldararo, 2004; Heinberg, 2004), and (b) sustainability will result automatically if we do so. Sustainability emerges, in this view, as a passive consequence of consuming less. Thus sustainability efforts are commonly focused on reducing consumption through voluntary or enforced conservation, perhaps involving simplification, and/or through improvements in technical efficiencies.

The common perspective on sustainability follows logically from the progressivist view that resources precede and facilitate innovations that increase complexity. Complexity, in this view, is a voluntary matter. Human societies became more complex by choice rather than necessity. By this reasoning, we should be able to choose to forego complexity and the resource consumption that it entails. Progressivism leads to the notion that societies can deliberately reduce their consumption of resources and thus achieve sustainability. Regrettably, we know that progressivism is a flawed argument, failing to provide an accurate account of history.

The fact that complexity and costliness increase through mundane problem solving suggests a different conclusion with a startling implication: Contrary to what is typically advocated as the route to sustainability, *it is usually not possible for a society to reduce its consumption of resources voluntarily over the long term*. To the contrary, as problems great and small inevitably arise, addressing these problems requires complexity and resource consumption to increase. Historically, as illustrated by the Roman Empire and other cases (Tainter, 1988, 2000, 2002, 2006; Allen *et al.*, 2003), this has commonly been the case.

The Byzantine collapse becomes important at this point. It is the only case of which I am aware in which a large, complex society systematically simplified, and reduced thereby its consumption of resources. While this case shows that societies can reduce resource consumption and thrive, it offers no hope that this can be done commonly. In the Byzantine case simplification was forced, made necessary by a gross insufficiency of revenues. The Byzantines undertook simplification and conservation because, to use a colloquial expression, their backs were to the wall. The empire had no choice. The Byzantine simplification was also temporary. As Byzantine finances recovered, emperors again expanded the size and complexity of their armed forces (McGeer, 1995; Treadgold, 1995). The Byzantine chronicler Anna Comnena, daughter of emperior Alexius I (1081–1118), described her father's marching army as like a moving city (Haldon, 1999).

Many students of sustainability will find it a disturbing conclusion that long-term conservation is not possible, contravening as it does so many assumptions about future sustainability. Naturally we must ask: are there alternatives to this process? Can we find a way out of this dilemma? Regrettably, as Boulding observed, no simple solutions are evident. Consider some of the approaches commonly advocated:

1. *Voluntarily Reduce Resource Consumption*. While this may work for a time, its longevity as a strategy is constrained by the factors discussed in this essay: Societies increase in complexity to solve problems, becoming more costly in the process. Resource production must subsequently increase to fund the increased complexity. To implement voluntary conservation long term would require that a society be either uniquely lucky in not being challenged by problems, or that it not address the problems that confront it. The latter strategy would at best reduce the legitimacy of the problem-solving institution, and at worst lead to its demise.

I will not address in depth the question whether long-term voluntary conservation is possible at the level of individuals and households. I am confident that usually it is not, that humans will not ordinarily forego affordable consumption of things they desire on the basis of abstract projections about the future. I raise the possibility of voluntary conservation only because of its perennial popularity.

There are societies that seem to incorporate an ethic of conservation. Japan, as described by Caldararo (2004), may be such a society. Caldararo argues that Japan participates in the system of industrial nations in its own way: low fertility, comparatively low consumption, high savings, acceptance of high prices, and tolerance of institutions that are economically inefficient but socially rational. "Japan," Caldararo believes, "is building a sustainable economy for the 21st century" (2004). Yet even if Caldararo's assessment is accurate, such a case does not contravene the arguments presented here. Even in societies that do voluntarily consume less than they could, problem solving must in time cause complexity, costliness, and resource consumption to grow. These things may grow from a smaller base, but the fundamental process of increasing complexity remains unaltered.

2. *Employ the Price Mechanism to Control Resource Consumption*. This is currently the *laissez-faire* strategy of industrialized nations. Since humans don't commonly forego affordable consumption of desired goods and services, economists consider it more effective than voluntary conservation. Both approaches, however, lead eventually to the same outcome: As problems arise, resource consumption must increase at the societal level even if consumers as individuals purchase less.

3. *Ration Resources*. Because of its unpopularity, rationing is possible in democracies only for clear, short-term emergencies. This is illustrated by the reactions to rationing in England and the

United States during World War II. Moreover, rationed resources may become needed to solve societal problems, belying any attempt to conserve through rationing. Something like this can be seen in the fiscal stimulus programs enacted in late 2008 and early 2009.

4. *Reduce Population*. While this would reduce aggregate resource consumption temporarily, as a long-term strategy it has the same fatal flaw as the first two: Problems will emerge that require solutions, and those solutions will compel resource production to grow.

5. *Hope for Technological Solutions*. I sometimes call this a faith-based approach to our future. We members of industrialized societies are socialized to believe that we can always find a technological solution to resource problems. Technology, within the framework of this belief, will presumably allow us continually to reduce our resource consumption per unit of material well-being. Conventional economics teaches that to bring this about we need only the price mechanism and unfettered markets. Consider, for example, the following statements:

- No society can escape the general limits of its resources, but no innovative society need accept Malthusian diminishing returns (Barnett and Morse, 1963),
- All observers of energy seem to agree that various energy alternatives are virtually inexhaustible (Gordon, 1981),
- By allocation of resources to R&D, we may deny the Malthusian hypothesis and prevent the conclusion of the doomsday models (Sato and Suzawa, 1983).

Our society's belief in technical solutions is deeply ingrained.

The flaw here was pointed out by Jevons (1866), as noted above: as technological improvements reduce the cost of using a resource, total consumption will eventually increase. The Jevons Paradox (also known as the Rebound Effect) is widely in effect (Polimeni *et al*., 2008), among economic levels ranging from nations to households and individuals, including in many sectors of daily life (Tainter, 2008).

Thus, conventional solutions to problems of resource consumption can only be effective for short periods of time. Over the long term, problem solving compels societies to grow in complexity and increase consumption. Because of this it is useful to think of sustainability in the metaphor of an athletic game: it is possible to "lose"—that is, to become unsustainable, as happened to the Western Roman Empire. But the converse does not hold. Because we continually confront challenges, there is no point at which a society has "won"—become sustainable in perpetuity, or at least for a very long time. Success, rather, consists of remaining in the game.

What can societies do when faced with increasing complexity, increasing costs, and diminishing returns in problem solving? There appear to be seven possible strategies, *all of which are effective only for a time* (Tainter, 2006). These are not sequential steps, nor are they mutually exclusive. They are simply ideas that can work alone or in combination. Some of these strategies would clearly have only short-term effects, while others may be effective for longer. The first strategy, however, is essential in all long-term efforts toward sustainability.

1. *Be aware*. Complexity is most insidious when the participants in an institution are unaware of what causes it. Managers of problem-solving institutions gain an advantage by understanding how complexity develops, and its long-term consequences. It is important to understand that unsustainable complexity may emerge over periods of time stretching from years to millennia, and that cumulative costs bring the greatest problems.

2. *Don't solve the problem*. This option is deceptively simple. As obvious as it seems, not solving problems is a strategy that is rarely adopted. The world view of Western industrial societies is that ingenuity and incentives can solve all problems. Ignorance of complexity, combined with the fact that the cost of solving problems is often deferred or spread thinly, reinforces our problem-solving inclination. Yet often we do choose not to solve problems, either because of their cost or because of competing priorities. Appropriators and managers do this routinely.

3. *Accept and pay the cost of complexity*. This is a common strategy, perhaps the most common in coping with complexity. It too is deceptively simple. Governments are often tempted to pay the cost of problem solving by increasing taxes, which reduces the share of national income available to other economic sectors. Businesses may do the same by increasing prices. The problem comes when taxpayers and consumers rebel, or when a firm's competitors offer a similar product at a lower cost.

4. *Find subsidies to pay costs*. This has been the strategy of modern industrial economies, which have employed the subsidies of fossil and nuclear energy to support our unprecedented levels of complexity. As seen since the adoption of coal (Wilkinson, 1973), the right subsidies can sustain complex problem solving for centuries. Anxiety over future energy is not just about maintaining a standard of living. It also concerns our future problem-solving abilities.

5. *Shift or defer costs*. This is one of the most common ways to pay for complexity. Budget deficits, currency devaluation, and externalizing costs exemplify this principle in practice. This was the strategy of the Roman Empire in debasing its currency, which shifted to the future the costs of containing current crises. Governments before the Roman Empire also practiced this subterfuge, as have many since. As seen in the case of the Romans, it is a strategy that can work only for a time. When it is no longer feasible, the economic repercussions may be far worse than if costs had never been deferred.

6. *Connect costs and benefits*. If one adopts the explicit goal of controlling complexity, costs and benefits must be connected so explicitly that the tendency for complexity to grow can be constrained by its costs. In an institution this means that information about the cost of complexity must flow accurately and effectively. Yet in a hierarchical institution, the flow of information from the bottom to the top is frequently inaccurate and ineffective (McIntosh *et al*., 2000). Thus the managers of an

institution are often poorly informed about the cost of complexity and feel free to deploy more.

7. *Recalibrate or revolutionize the activity*. This involves a fundamental change in how costs and benefits are connected, and is potentially the most far-reaching technique for coping with complexity. The strategy may involve both new resources and new types of complexity that lower costs, combined with positive feedback among new elements that amplifies benefits and produces growth. As noted above, true revolutions of this sort are rare, so much so that we recognize them in retrospect with a term signifying a new era: the Agricultural Revolution and the Industrial Revolution. Today's Information Revolution may be another such case. Fundamental changes of this sort depend on opportunities for positive feedback, where elements reinforce each other. For example, Watt's steam engine facilitated the mining of coal by improving pumping water from mines. Cheaper coal meant more steam engines could be built and put to use, facilitating even cheaper coal (Wilkinson, 1973). Put a steam engine on rails and both coal and other products can be distributed better to consumers. Combine coal, steam engines, and railroads, and we had most of the components of the Industrial Revolution, all mutually reinforcing each other. The economic system became more complex, but the complexity involved new elements, connections, and subsidies that produced increasing returns.

The transformation of the U.S. military since the 1970s provides a more recent example. So profound is this transformation that it is recognized by its own acronym: RMA, the revolution in military affairs. The revolution involves extensive reliance on information technology, as well as the integration of hardware, software, and personnel. Weapons platforms are just part of this revolution, since weapons now depend on integration with sensors, satellites, software, and command systems (Paarlberg, 2004). This is a military that is vastly more complex than ever before. That complexity is of course costly, but the benefits include both greater effectiveness and significant cost savings. Being able to pinpoint targets means less waste of ordinance, less need for large numbers of weapons platforms, and a need for fewer people.

The fact that such revolutions do occur gives hope that a way out of our current dilemma may be found. Yet complex systems at the societal level cannot be designed. They emerge on their own or they don't. To rely on some hoped-for revolution involving innovation, energy, and positive feedback is, like relying on technological innovation, a faith-based approach to our future.

V. CONCLUDING REMARKS

Sustainability is not the achievement of stasis. It is not a passive consequence of having fewer humans who consume more limited resources. One must work at being sustainable. The challenges to sustainability that any society (or other institution) might confront are, for practical purposes, endless in number and infinite in variety. This being so, sustainability is a matter of problem solving, an activity so commonplace that we perform it with little thought to its long-term implications.

The notion of progress is ingrained in industrial societies, so much so that it is part of our cosmology, a fundamental element of our ancestor myth. Just as our ancestors, we believe, "pulled themselves up" through ingenuity, so today we continue this tradition. In the conventional framework, all that past societies required for innovation and progress was free time emerging from a sufficient level of energy and other resources. Complexity, it is believed, follows energy, and if this is so then we should be able to forego complexity voluntarily and reduce our consumption of the resources that it requires. This is the conventional approach to sustainability, which implicitly sees the future as a condition of stasis with no challenges.

In actuality, major infusions of surplus energy are rare in human history. More commonly, complexity increases in response to problems, problems that are sometimes large-scale and urgent. Increased complexity requires increased resources, although when a problem is addressed long-term costs are typically not considered fully. Complexity emerging through problem solving typically precedes the availability of energy, and compels increases in its production. Energy follows complexity. Complexity is not voluntary, nor is it something that we can ordinarily choose to forego. Complexity is required to solve problems.

Applying this understanding to the problem of sustainability leads to two conclusions that are not presently recognized in the sustainability movement. The first is that the solutions commonly recommended to promote sustainability—conservation, simplification, pricing, and innovation—can do so only in the short term. Secondly, long-term sustainability depends on solving major societal problems that will converge in coming decades, and this will require increasing complexity and energy production. Sustainability is demonstrably not a condition of stasis. It is, rather, a process of continuous adaptation, of perpetually addressing new or ongoing problems and securing the resources to do so. Developing new energy is therefore the most fundamental thing we can do to become sustainable.

REFERENCES

9/11 Commission. 2004. *The 9/11 Commission Report: Final Report of the National Commission on Terrorist Attacks Upon the United States*. Norton, New York.

Allen, T. F. H., Tainter, J. A., and Hoekstra, T. W. 2003. *Supply-Side Sustainability*. Columbia University Press, New York.

Atkinson, R. 2002. *An Army at Dawn: The War in North Africa, 1942–1943*. Henry Holt, New York.

Barnett, H. J. and Morse, C. 1963. *Scarcity and Growth: The Economics of Natural Resource Availability*. Johns Hopkins Press, Baltimore.

Boak, A. E. R. 1955. *Manpower Shortage and the Fall of the Roman Empire in the West*. University of Michigan Press, Ann Arbor.

Boserup, E. 1965. *The Conditions of Agricultural Growth: the Economics of Agrarian Change under Population Pressure*. Aldine, Chicago.

Boulding, K. E. 1959. Foreward. In: *Population: The First Essay*. pp. v-xii. Malthus, T. R., University of Michigan Press, Ann Arbor.

Bronowski, J. 1973. *The Ascent of Man*. Little, Brown, Boston.

Brown, L. R. 2008. *Plan B 3.0: Mobilizing to Save Civilization*. W. W. Norton, New York.

Caldararo, N. 2004. *Sustainability, Human Ecology, and the Collapse of Complex Societies: Economic Anthropology and a 21st Century Adaptation*. Mellen Studies in Anthropology 15. Edward Mellen Press, Lewiston, NY..

Catton, W. R. 1980. *Overshoot: the Ecological Basis of Revolutionary Change*. University of Illinois Press, Urbana.

Childe, V. G. 1944. *Progress and Archaeology*. Watts and Company, London.

Childe, V. G. 1951. *Man Makes Himself* (revised edition). Mentor, New York.

Clark, C. and Haswell, M. 1966. *The Economics of Subsistence Agriculture*. MacMillan, London.

Cohen, M. N. 1977. *The Food Crisis in Prehistory: Overpopulation and the Origins of Agriculture*. Yale University Press, New Haven.

Diamond, J. 1997. *Guns, Germs, and Steel: The Fates of Human Societies*. W. W. Norton, New York.

Diamond, J. 2005. *Collapse: How Societies Choose to Fail or Succeed*. Viking, New York.

Duncan-Jones, R. 1990. *Structure and Scale in the Roman Economy*. Cambridge University Press, Cambridge.

Ehrlich, P. R. 1968. *The Population Bomb*. Ballantine, New York.

Farb, P. 1978. *Man's Rise to Civilization: The Cultural Ascent of the Indians of North America* (2nd edition). E. P. Dutton, New York.

Gordon, R. L. 1981. *An Economic Analysis of World Energy Problems*. Massachusetts Institute of Technology Press, Cambridge.

Haldon, J. F. 1990. *Byzantium in the Seventh Century: The Transformation of a Culture*. Cambridge University Press, Cambridge.

Haldon, J. F. 1999. *Warfare, State and Society in the Byzantine World*, 565–1204. UCL Press, London.

Harl, K. W. 1996. *Coinage in the Roman Economy, 300 B.C. to A.D. 700*. Johns Hopkins University Press, Baltimore.

Heinberg, R. 2004. *Power Down: Options and Actions for a Post-Carbon World*. Gabriola Island, BC, New Society Publishers.

Hodgett, G. A. J. 1972. *A Social and Economic History of Medieval Europe*. Methuen, London.

Jevons, W. S. 1866. *The Coal Question: An Inquiry Concerning the Progress of the Nation and the Probably Exhaustion of Our Coal-Mines* (second edition). London, Macmillan.

Jones, A. H. M. 1964. *The Later Roman Empire, 284–602: A Social, Economic and Administrative Survey*. University of Oklahoma Press, Norman.

Jones, A. H. M. 1974. *The Roman Economy: Studies in Ancient Economic and Administrative History*. Basil Blackwell, Oxford.

MacMullen, R. 1976. *Roman Government's Response to Crisis, A.D. 235–337*. Yale University Press, New Haven.

Malthus, T. R. 1798. *An Essay on the Principle of Population*. J. Johnson, London.

McGeer, E. 1995. *Sowing the Dragon's Teeth: Byzantine Warfare in the Tenth Century*. Dumbarton Oaks Studies XXXIII. Dumbarton Oaks, Washington, DC.

McGuire, R. H. 1983. *Breaking down cultural complexity: inequality and heterogeneity*. **In**: Advances in Archaeological Method and Theory. Volume 6. pp. 91–142. Schiffer, M. B., Ed., Academic Press, New York.

McIntosh, R. J., Tainter, J. A., and McIntosh, S. K. 2000. *Climate, history, and human action*. In: The Way the Wind Blows: Climate, History, and Human Action. pp. 1–42. McIntosh, R. J., Tainter, J. A., and McIntosh, S. K., Eds., Columbia University Press, New York.

Paarlberg, R. L. 2004. *Knowledge as power: science, military dominance, and U.S. security*. International Security 29: 122–51.

Polimeni, J. M., Mayumi, K. Giampietro, M., and Alcott, B. 2008. *The Jevons Paradox and the Myth of Resource Efficiency Improvements*. Earthscan, London.

Russell, J. C. 1958. *Late ancient and medieval population. Transactions of the American Philosophical Society* **48(3)**.

Sato, R., and Suzawa, G. S. 1983. *Research and Productivity: Endogenous Technical Change*. Auburn House, Boston.

Steward, J. H. 1955. *Theory of Culture Change*. University of Illinois Press, Urbana.

Tainter, J. A. 1988. *The Collapse of Complex Societies*. Cambridge University Press, Cambridge.

Tainter, J. A. 1994. *La fine dell'amministrazione centrale: il collaso dell'Impero Romano in Occidente*. In: Storia d'Europa, Volume Secondo: Preistoria e Antichità. pp. 1207–1255. Guilaine, J. and Settis, S., Eds., Einaudi, Turin.

Tainter, J. A. 1996. *Complexity, problem solving, and sustainable societies*. In: Getting Down to Earth: Practical Applications of Ecological Economics. pp. 61–76. Costanza, R., Segura, O., and Martinez-Alier, J., Eds., Island Press, Washington, DC.

Tainter, J. A. 1999. *Post-Collapse Societies*. In: Companion Encyclopedia of Archaeology, pp. 988–1039. Barker, G., Ed. Routledge, London.

Tainter, J. A. 2000. *Problem solving: Complexity, history, sustainability*. Population and Environment **22**: 3–41.

Tainter, J. A. 2002. A framework for archaeology and sustainability. **In**: *Encyclopedia of Life Support Systems*. EOLSS Publishers, Oxford. [online] http://www.eolss.net.

Tainter, J. A. 2005. *Perspective on Diamond's Collapse: How Societies Choose to Fail or Succeed*. Current Anthropol. **46**: S97–S99.

Tainter, J. A. 2006. *Social Complexity and Sustainability*. Ecological Complexity **3**: 91–103.

Tainter, J. A. 2008. *Foreword*. In: The Jevons Paradox and the Myth of Resource Efficiency Improvements. pp. ix–xvi. Polimeni, J. M., Mayumi, K., Giampietro, M., and Alcott, B., Authors, Earthscan, London.

Tainter, J. A. and Crumley, C. L. 2007. *Climate, complexity, and problem solving in the Roman Empire*. In: Sustainability or Collapse? An Integrated History and Future of People on Earth. pp. 61–75. Costanza, R., Graumlich, L. J., and Steffen, W., Eds. Dahlem Workshop Report 96. The MIT Press, Cambridge.

Treadgold, W. 1988. *The Byzantine Revival, 780–842*. Stanford University Press, Stanford.

Treadgold, W. 1995. *Byzantium and its Army, 284–1081*. Stanford University Press, Stanford.

Treadgold, W. 1997. *A History of the Byzantine State and Society*. Stanford University Press, Stanford.

Van Meter, D. 1991. *The Handbook of Roman Imperial Coins*. Laurion Numismatics, Nashua, NH.

Wallace, R. 1761. *Various Prospects of Mankind, Nature, and Providence*. A. Millar, London.

Wickham, C., 1984. *The other transition: from the ancient world to feudalism*. Past and Present **103**: 3–36.

Wilkinson, R. G. 1973. *Poverty and Progress: an Ecological Model of Economic Development*. Methuen, London.

Williams, S. 1985. *Diocletian and the Roman Recovery*. Methuen, New York.

Critical Reviews in Plant Sciences, 30:35–44, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554349

Food for Thought: A Review of the Role of Energy in Current and Evolving Agriculture

David Pimentel
College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853, USA

Table of Contents

World malnutrition is a serious problem. Food security for the poor depends on an adequate supply of food and/or the ability to purchase food. The World Health Organization reports that more than 3.7 billion people worldwide are malnourished because of shortages of calories, protein, several vitamins, iron, and iodine. People can die because of shortages of any one or a combination of these nutrients. In the world today there are more than 6.8 billion humans. Based on current rates of increase, the world population is projected to double to more than 13 billion in about 58 years. At a time when the world population continues to expand at a rate of 1.2% per year, adding more than a quarter million people daily, providing adequate food becomes an increasingly difficult problem. The need to increase and make more rational food production, to conserve natural resources, and to reduce food (crop) losses to pests is critical. Also critical is a need to reduce human population numbers. Cropland, water and energy resources are inadquate to support the current 6.8 billion people on earth.

Keywords conservation, diet, ecological agriculture, energy, sustainable agriculture, malnutrition, natural resources, nutrients

I. GLOBAL FOOD IMBALANCES

A. World Malnutrition

Currently, food shortages are critical with more than 3.7 billion humans malnourished worldwide (nearly 60% of the world population). This is the largest number of malnourished ever (Neisheim, 1993; McMichael, 1993; WHO, 2005). Nearly 10 million children under the age of 5 die each year (more than 1,000 every hour) due to malnutrition and other diseases (Rehydration Project, 2007).

The current world population is about 6.8 billion. Based on the present growth rate of 1.2% per year, the population is projected to double to 13 billion in approximately 58 years (PRB,

---

Address correspondence to David Pimentel, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853, USA. E-mail: dp18@cornell.edu.

Referee: Albert A. Bartlett, Professor Emeritus of Physics, University of Colorado at Boulder, Boulder, CO, USA.

2008). Because population growth cannot continue indefinitely, society can either voluntarily control its numbers or let natural forces such as disease, malnutrition, and other disasters limit human numbers (Bartlett, 1998; Pimentel *et al*., 1999). Increasing human numbers, especially in urban areas, and increasing food, water, air, and soil pollution by pathogenic disease organisms and chemicals, are causing a rapid increase in the prevalence of disease and number of human deaths (WHO, 1992; Murray and Lopez, 1996; Pimentel *et al*., 2007).

The planet's numerous environmental problems emphasize the urgent need to evaluate the available food, agriculture, and natural resources and how they relate to the requirements of a rapidly growing human population (Pimentel and Pimentel, 2008). In this article, the socioeconomic performance and carring capacity of ecological agriculture is evaluated. In addition, I suggest appropriate policies and technologies that would improve agriculture and the standard of living and quality of life worldwide.

B. Over Consumption of Food in the U.S.

The average American consumes 1,000 kg (2,200 lbs) of food per person per year containing and estimated 3,747 kcal per day (Table 1).

A vegetarian diet of an equivalent 3,747 kcal per day requires 33% less fossil energy than the average American diet with meat (Pimentel and Pimentel, 2008). The Food and Drug Administration (Pimentel and Pimentel, 2008) recommends an average daily consumption of 2,000 for females and 2,500 kcal for males per day, much less than the average American is presently consuming. Reducing the calorie intake to a lower level would significantly reduce the energy used in food production as well as reduce the obesity problem.

The fossil energy required to produce the relatively high level of animal products consumed in the average American diet are estimated to be about 50% of the total energy inputs, whereas to produce the staple foods such as, potatoes, wheat, common vegetables and fruits, uses about 20% of the fossil energy inputs

TABLE 1
Current U.S. food consumption of 3,747 kcal per day and a recommended food consumption of 2,503 kcal per day without junk foods included in either diet (FAO, 2004).

	Current Diet		Reduced Consumption Diet		
Food	kcal/day	kg/year	% reduction	kg/year	kg/year
Grains	1509	157	15	1283	133
Starchy roots	136	63	15	116	54
Sweeteners	282	140	65	100	49
Nuts	15	2	0	15	2
Fats & Oils	581	86	65	203	30
Vegetables	80	131	0	80	131
Fruits	126	124	0	126	124
Meat	526	94	50	263	47
Fish	28	21	50	14	11
Milk	403	241	40	242	145
Eggs	61	17	0	61	17
Total	**3747**	**1076**		**2503**	**743**
	Lacto-ovo Diet				
Food	kcal/day	kg/year	% reduction	kcal/day	kg/year
Grains	1579.75	164.36	45	865	89.67
Starchy Roots	264.5	122.29	12	230	107.07
Sweeteners	282	140	51	100	49
Nuts	100	13.33	0	100	13.33
Fats & Oils	168.3	24.91	39	102	15.07
Vegetables	222	363.53	0	222	363.53
Fruits	234	230.285	0	234	230.29
Meat	0	0	100	0	0
Fish	28	21	100	0	0
Milk	560.2	335	3	543	325.35
Eggs	204	56.85	0	204	56.85
Total	**3614.75**	**1565.6**		**2500**	**1250.16**

(Pimentel *et al*., 2008) (Table 1). These data differ from the thoroughly studied Dutch diet where staple foods account for 12% of the total energy input and animal products for another 36% of the energy (Gerbens-Leenes *et al*., 2002).

Based on preliminary data, Block (2004) estimates that the average American consumes 33% of their total calories in junk food. Reducing junk food intake from 33% of the calories to 10% would reduce the caloric intake to 2,826 kcal, while at the same time conserving energy and improving human health (Table 2). Consider that a kilogram of potato chips has 5,667 kcal of food energy, whereas a kilogram of potatoes has only 548 kcal of food energy (USDA, 1976).

II. LIMITED AGRICULTURAL RESOURCES

A. Shortages of Cropland

More than 99.7% of human food (calories) in the world comes from the terrestrial environment; less than 0.3% comes from the oceans and other aquatic ecosystems (FAO, 2004). Worldwide, food and fiber crops are grown on 11% of the Earth's total land area of 13 billion hectares. Globally, the annual loss of land to urbanization and highways ranges from 10 to 35 million hectares (approximately 1%) per year, with half of this lost land coming from cropland (Doeoes, 1994). Most of the remaining land area (23%) apart from that occupied by cropland, pasture, and forest is unsuitable for crops, pasture, and forests because the soil is too infertile or shallow to support plant growth, or the climate and land are too cold, dry, steep, stony, or wet.

In 1960, when the world population numbered about 3 billion, approximately 0.5 ha of cropland was available per capita worldwide. This half a hectare of cropland per capita is needed to provide a diverse, healthy, nutritious diet of plant and animal products—similar to the typical diet in the United States and Europe (Lal, 1989; Giampietro and Pimentel, 1994). The average per capita world cropland now is only 0.22 ha, or about half the amount needed according to industrial nation standards (Table 3).

This shortage of productive cropland is one underlying cause of the current worldwide food shortages and poverty (Leach, 1995; Pimentel and Pimentel, 2008). For example, in China, the amount of available cropland is only 0.1 ha per capita, and rapidly declining due to continued population growth and extreme land degradation. This minute amount of arable land forces the Chinese people to consume primarily a vegetarian diet (Table 3).

TABLE 2
Junk foods consumed per person and proposed reduction.

Item	Quantity	Energy × 1000 kcal	Reduced	Energy × 1000 kcal
Soft drinks	600 cans[1]	1,300	100 cans	220
Potato chips	7.2 kg[2]	35	1 kg	4.8
Popcorn	25 kg[3]	113	2 kg	9.2

[1] 12-oz. cans. (Valentine, 2006).
[2] Kuchler *et al*., 2004.
[3] Coelho, 2006.

TABLE 3
Resources used and/or available per capita per year in the United States, China, and the world to supply the basic needs of humans (FAO, 2004).

Resources	U.S.	China	World
Land			
Cropland (ha)	0.59	0.10	0.22
Pasture (ha)	0.79	0.30	0.52
Forest (ha)	1.01	0.15	0.61
Total	3.06	0.71	2.00
Water (liters × 10^6)	1.7	0.45	0.60
Fossil fuel oil equivalents (liters)	9500	700	2100

Currently, a total of 1,500 kg/yr per capita of agricultural products is produced to feed Americans, while the Chinese food supply averages 800 kg/yr per capita. By all measurements, the Chinese have reached or exceeded the limits of their agricultural system (Pimentel and Wen, 2004). Their reliance on large inputs of fossil-fuel based fertilizers—as well as other limited inputs—to compensate for shortages of arable land and severely eroded soils, indicates severe problems for the future (Wen and Pimentel, 1992). The Chinese already import large amounts of grain from the United States and other nations and are planning to increase these imports in the future.

Escalating land degradation threatens most crop and pasture land throughout the world (Pimentel *et al.*, 1995; Pimentel, 2006). The major types of degradation include water and wind erosion, and the salinization and water-logging of irrigated soils (Kendall and Pimentel, 1994). Worldwide, more than 10 million hectares of productive arable land are severely degraded and abandoned each year (Pimentel, 2006). Moreover, an additional 5 million hectares of new land must be put into production each year to feed the nearly 90 million humans annually added to the world population. Most of the 15 million hectares needed yearly to replace lost land is coming from the world's forests (WRI, 1996). The urgent need for more agricultural land accounts for more than 60% of the deforestation now occurring worldwide (Myers, 1990).

Agricultural erosion by wind and water is the most serious cause of soil loss and degradation. Current erosion rates are greater than ever previously recorded (Pimentel, 2006). Soil erosion on cropland ranges from about 13 tons per hectare per year (t/ha/yr) in the United States to 40 t/ha/yr in China (Pimentel and Wen, 2004). Worldwide, soil erosion averages approximately 30 to 40 t/ha/yr, or about 30 to 40 times faster than the replacement rate (Pimentel, 2006). During the past 30 years, the rate of soil loss in Africa has increased 20-fold (Tolba, 1989). Wind erosion is so serious in China that Chinese soil can be detected in the Hawaiian atmosphere during the spring planting period

(Parrington *et al.*, 1983). Similarly, soil eroded by wind in Africa can be detected in Florida and Brazil each year (Pimentel *et al.*, 2000).

Erosion adversely affects crop productivity by reducing the water-holding capacity of the soil, water availability, nutrient levels and organic matter in the soil, and soil depth (Pimentel *et al.*, 1995). Estimates are that agricultural land degradation alone can be expected to depress world food production between 15% and 30% by the year 2020 (Pimentel *et al.*, 2000). These estimates emphasize the need to implement known soil conservation techniques, including biomass mulches, no-till, ridge-till, terracing, grass strips, crop rotations, and combinations of all of these. All these techniques essentially require keeping the land protected from wind and rainfall effects with some form of vegetative cover (Pimentel, 2006).

The current high erosion rate throughout the world is of great concern because of the slow rate of topsoil renewal; it takes approximately 500 years for 2.5 cm (1 inch) of topsoil to form under agricultural conditions (Troeh *et al.*, 2004). Approximately 3,000 years are needed for the natural reformation of topsoil to the 150 mm depth needed for satisfactory crop production.

The fertility of nutrient-poor soil can be improved by large inputs of fossil-based fertilizers. This practice, however, increases dependency on the limited fossil fuels stores necessary to produce these fertilizers. And even with fertilizer use, soil erosion remains a critical problem in current agricultural production (Pimentel and Pimentel, 2008). Crops can be grown under artificial conditions using hydroponic techniques, but the costs in terms of energy and dollars is approximately 10 times that of conventional agriculture (Schwarz, 1995).

The arable land currently used for crop production already includes a considerable amount of marginal land, land that is highly susceptible to erosion. When soil degradation occurs, the requirement for fossil energy inputs in the form of fertilizers, pesticides, and irrigation is increased to offset the losses, thus creating non-sustainable agricultural systems (Pimentel *et al.*, 1995; Lal, 1998).

If the U.S. population were reduced from the current 311 million to 100 million, the per capita cropland would increase to about 1.5 ha (USDA, 2007). Using more crop rotations and other types of soil conservation technologies will require additional cropland. Still the U.S. should have ample cropland available for food production.

B. Water Resources

The present and future availability of adequate supplies of freshwater for human and agricultural needs is already critical in many regions, like the Middle East (Postel, 1997). Rapid population growth and increased total water consumption are rapidly depleting the availability of water. Between 1950 and 1995, the per capita availability of freshwater worldwide declined by about 70% (Gleick, 2009).

All vegetation requires and transpires massive amounts of water during the growing season. Agriculture commands more water than any other activity on the planet. It is estimated that 70% to 85% of water removed from all sources worldwide is used solely for irrigation (Gleick, 2000; UNESCO, 2001). Of this amount, about two-thirds is consumed by plant life (nonrecoverable) (Postel, 1997). For example, a corn crop that produces about 9,000 kg/ha of grain uses more than 7 million liters/ha of water during the growing season (Pimentel and Pimentel, 2008). To supply this much water to the crop, approximately 1,000 mm of rainfall per hectare, or 10 million liters of irrigation, is required during the growing season.

The minimum amount of water required per capita for food is about 400,000 liters per year worldwide and in the United States the average amount of water consumed annually in food production is 1.7 million liters per capita per year (Postel, 1996; USDA, 1996). Most of the 1.7 million liters is for irrigated food production. We suggest that the 1.7 million liters be reduced to 500,000 liters per year with a reduction of about 90% of the current irrigation.

The minimum basic water requirement for human health, including drinking water, is 50 liters per capita per day (Gleick, 1996). The U.S. average for domestic usage, however, is 8 times higher than that figure, at 400 liters per capita per day.

Water resources and population densities are unevenly distributed worldwide. Even though the *total* amount of water made available by the hydrologic cycle is enough to provide the world's current population with adequate fresh water—according to the *minimum* requirements cited above—most of this total water is concentrated in specific regions, leaving other areas water-deficient. Water demands already far exceed supplies in nearly 80 nations of the world (Gleick, 1993). In China, more than 300 cities suffer from inadequate water supplies, and the problem is intensifying as the population increases (Berk and Rothenberg, 2003). In arid regions, such as the Middle East and parts of North Africa, where yearly rainfall is low and irrigation is expensive, the future of agricultural production is grim and becoming more so as populations continue to grow. Political conflicts over water in some areas, such as the Middle East, have even strained international relations between severely water-starved nations (Gleick, 1993).

The greatest threat to maintaining fresh water supplies is depletion of the surface and groundwater resources that are used to supply the needs of the rapidly growing human population. Surface water is not always managed effectively, resulting in water shortages and pollution that threaten humans and the aquatic biota that depend on it. The Colorado River, for example, is used so heavily by Colorado, California, Arizona, and other states, that by the time the river reaches Mexico, it is usually no more than a trickle running into the Gulf of California.

Groundwater resources are also mismanaged and overtapped. Because of their slow recharge rate, usually between 0.1% to 0.3% per year (UNEP, 1991; Covich, 1993), groundwater resources must be carefully managed to prevent depletion. Yet, humans are not effectively conserving groundwater resources. In Tamil Nadu, India, groundwater levels declined 25 to 30 m during the 1970s as a result of excessive pumping for irrigation (UNFPA, 1991; Pimentel *et al*., 2002). In Beijing, the groundwater level is falling at a rate of about 1 m/yr; while in Tianjin, China, it drops 4.4 m/yr (Postel, 1997). In the United States, aquifer overdraft averages 25% higher than replacement rates. In an extreme case like the Ogallala aquifer under Kansas, Nebraska, and Texas, the annual depletion rate is 130% to 160% above replacement (Beaumont, 1985). In some parts of Arizona, water in some aquifers is being withdrawn 10 times faster than the recharge rate (Gleick *et al*., 2002).

High consumption of surface and groundwater resources, in addition to high implementation costs, is beginning to limit the option of irrigation in arid regions. Furthermore, salinized and waterlogged soils – both soil problems that result from continued irrigation require attention in the U.S. It is estimated that about 10 million ha of cropland is being abandoned per year due to salinization (NAS, 2003).

Although no technology can double the flow of the Colorado River or enhance other surface and ground water resources, improved environmental management and conservation can increase the efficient use of available freshwater. For example, drip irrigation in agriculture can reduce water use by nearly 50% (O'Brien *et al*., 2008). In developing countries, though, equipment and installation costs, as well as limitations in science and technology, often limit the introduction and use of these more efficient technologies.

Desalinization of ocean water is not a viable source of the freshwater needed by agriculture, because the process is energy intensive and, hence, economically impractical. The amount of desalinized water required by 1 hectare of corn would cost $14,000, while all other inputs, like fertilizers, cost only $500 (Pimentel *et al.*, 1997). This figure does not even include the additional cost of moving large amounts of water from the ocean to inland agricultural fields.

Another major threat to maintaining ample fresh water resources is pollution. Considerable water pollution has been documented in the United States (USCB, 1998), but this problem is of greatest concern in countries where water regulations are less rigorously enforced or do not exist. Developing countries discharge approximately 95% of their untreated urban sewage directly into surface waters (WHO, 1993). Of India's 3,119 towns and cities, only 209 have partial sewage treatment facilities and a mere eight have full wastewater treatment facilities (WHO, 1992). A total of 114 cities dump untreated sewage and partially cremated bodies directly into the sacred Ganges River (NGS, 1995). Downstream, the polluted water is used for drinking, bathing, cooking, and washing. This situation is typical of many rivers and lakes in developing countries (WHO, 1992).

Overall, approximately 95% of the water in developing countries is polluted (WHO, 1992). There are, however, serious problems in the United States as well. EPA (1994) reports indicate that 40% of U.S. lakes are unfit for swimming due to runoff pollutants and septic tank discharge.

Pesticides, fertilizers, and soil sediments pollute water resources when they accompany eroded soil into a body of water. In addition, industries all over the world often dump untreated toxic chemicals into rivers and lakes (WRI, 1991; WHO, 1993). Pollution by sewage and disease organisms, as well as some 100,000 different chemicals used globally, makes water unsuitable not only for human drinking but also for application to crops (Nash, 1993). Although some new technologies and environmental management practices are improving pollution control and the use of resources, there are economic and biophysical limits to their use and implementation (Gleick, 1993).

C. Energy Resources

Over time, people have relied on various sources of power. These sources have ranged from human, animal, wind, tidal, and water energy, to wood, coal, gas, oil, and nuclear sources for fuel and power. Fossil fuel energy permits a nation's economy to feed an increasing number of humans, as well as improving the general quality of life in many ways, including protection from numerous diseases (Pimentel and Pimentel, 2008).

About 473 quads (1 quad $= 10^{15}$ BTU or $1{,}987 \times 10^{18}$ Joules) from all energy sources are used worldwide per year (International Energy Annual, 2007) (Table 4).

Current energy expenditure is directly related to many factors, including rapid population growth, urbanization, and high consumption rates. Increased energy use also contributes to environmental degradation (Pimentel and Pimentel, 2008). Energy use has been growing even faster than world population growth. From 1970 to 1995, energy use was increasing at a rate of 2.5% (doubling every 30 years) whereas the worldwide population only grew at 1.7% (doubling about 40 years) (PRB, 1996; International Energy Annual, 1995–2007). Current energy use is projected to increase at a rate of 2.2% (doubling every 32 years) compared with a population growth rate of 1.2% (doubling every 58 years) (PRB, 2008; International Energy Annual, 2007).

TABLE 4

Fossil and solar energy use in the U.S. and world (quads $= 10^{15}$BTU) (USCB 2007).

Fuel	U.S.	World
Petroleum	40.1	168
Natural gas	23.0	103
Coal	22.3	115
Nuclear	8.2	28
Biomass	3.0	30
Hydroelectric power	3.4	27
Geothermal and wind power	0.4	0.8
Biofuels	0.5	0.9
Total	100.9	472.7

Although about 50% of all the solar energy captured by photosynthesis worldwide is used by humans, it is still inadequate to meet all of the planet's needs for food worldwide (Pimentel and Pimentel, 2008). To make up for this shortfall, about 473 quads of fossil energy (oil, gas, and coal) are utilized worldwide each year (International Energy Annual, 2007). Of this, 109 quads are utilized in the United States (USCB, 2008). The U.S. population consumes 70% more fossil energy than all the solar energy captured by harvested U.S. crops, forest products, and other vegetation each year (Pimentel *et al*., 2008).

Industry, transportation, home heating, and food production account for most of the fossil energy consumed in the United States (USCB, 2008). Per capita use of fossil energy in the United States is 9,500 liters of oil equivalents per year, more than 13 times the per capita use in China (Table 3). In China, most fossil energy is used by industry, but a substantial amount, approximately 25%, is used for agriculture and the food system (Pimentel and Wen, 2004).

Developed nations annually consume about 70% of the fossil energy worldwide, while the *developing* nations, which have about 75% of the world population, use only 30% (International Energy Annual, 2007). The United States, with only 4.5% of the world's population, consumes about 25% of the world's fossil energy output (Pimentel and Pimentel, 2008). Fossil energy use in the different U.S. economic sectors has increased 20- to 1,000-fold in the past 3 to 4 decades, attesting to America's heavy reliance on this finite energy resource to support their affluent lifestyle (Pimentel *et al.*, 2004).

Several developing nations that have high rates of population growth are increasing fossil fuel use to augment their agricultural production of food and fiber. In China, there has been a 100-fold increase in fossil energy use in agriculture for fertilizers, pesticides, and irrigation since 1955 (Pimentel and Wen, 2004).

Fertilizer production on the whole, though, has declined by more than 22% since 1991, especially in the developing countries, due to fossil fuel shortages and high prices (IFIA, 2008). In addition, the overall projections of the availability of fossil energy resources for fertilizers and all other purposes are discouraging because of the limited stores of these fossil fuels.

World oil production has peaked and projections are that by 2040, oil will decline to about 62% below peak (W. Youngquist, Personal Communication, petroleum geologist, Eugene, Oregon, 30 April, 2008). The world supply of oil is projected to last approximately 40 to 60 years, if use continues at current production rates.Worldwide, the earth's natural gas supply is projected to peak at 2020 and coal peak at 2025. Natural gas and coal are considered adequate for about 100 years. In the U.S., natural gas supplies are already in short supply: it is projected that the United States will deplete its natural gas resources in about 40 years. Many agree that the world has reached peak oil in 2007; after this, oil resources will decline slowly and continuously until there are little or no oil resources left (Walter Youngquist, Personal Communication, 2009).

If we continue to hope that new discoveries of oil will postpone the arrival of the peak of oil production, we should remember that the peak moves back only at the rate of 5.5 days per billion barrels of oil that are added to the geological estimate of the world's total oil resource (Bartlett, 1998).

Youngquist (1997) reports that current oil and gas exploration drilling data has not borne out some of the earlier optimistic estimates of the amount of these resources yet to be found in the United States. Both the production rate and proven reserves have continued to decline. Domestic oil and natural gas production will be substantially less in 20 years than it is today. Neither is now sufficient for domestic needs, and supplies are imported yearly in increasing amounts (USBC, 2008). Analyses suggest that at present (2008) the United States has consumed about 90% of the recoverable oil that was ever in the ground, and that we are currently consuming the last 3% of our oil. The United States is now importing nearly 70% of its oil, which puts the U.S. economy at risk due to fluctuating oil prices and difficult political situations, such as the 1973 oil crisis and the 1991 Gulf War.

At present, electricity represents about 34% of total U.S. energy consumption (nuclear power contributes about 20% of the electric needs) (USBC, 2008). Nuclear production of electricity has some advantages over fossil fuels because its production requires less land than coal-fired plants and its use does not contribute to acid rain and global warming. Nuclear power, however, once seen as the future of electrical production, is currently suffering major economic difficulties. No new construction permits for nuclear power facilities have been issued in the United States during the past 25 years (Youngquist, 1997).

Nuclear *fusion* has long been the subject of major efforts, yet the goal of achieving commercial fusion power remains elusive even after 50 years of intense research. It seems unwise to depend on nuclear fusion for commercial energy, at least in the near future.

All of the chemical and nuclear energy that society consumes ultimately winds up as heat in the environment. The Second Law of Thermodynamics limits the efficiency of heat engines to about 35%. This means that approximately two-thirds of the potential energy in the fuel, whether chemical or nuclear, is converted into heat, while the remaining one-third is delivered as useful work (and, eventually, also converted into heat). Releasing this heat into the environment can have adverse effects on aquatic and terrestrial ecosystems (Bartlett, 1994).

More efficient end-use of electricity can reduce its costs, while at the same time reduce environmental impacts. Commercial, residential, industrial, and transportation sectors all have the potential to reduce energy consumption by approximately 33% while saving money (Pimentel *et al.*, 2004). Some of the necessary changes to reduce consumption would entail more efficiently designed buildings, appliances, and industrial systems (Pimentel *et al.*, 2004).

TABLE 5
Potential renewable energy for U.S.

Energy Technology	Current Quads	Projected (2100) Quads[c]
Biomass	3.3[a]	7
Hydroelectric	2.9[a]	5
Geothermal	0.3[a]	3
Solar thermal	0.06[b]	10
Photovoltaics	0.06[b]	10
Wind power	0.3[a]	8
Biogas	0.001[b]	0.5
TOTAL	6.8	43.5

[a] EIA, 2007.
[b] USCB, 2008.
[c] Calculated from Pimentel (2008).

Using available renewable energy technologies, such as biomass and wind power, an estimated 44 quads of energy can be supplied in the U.S. with the full implementation of 7 different renewable energy technologies (Table 5) (Pimentel, 2008). For the world I estimate about 200 quads of renewable energy could be produced worldwide from 20% to 25% of the land area. A self-sustaining renewable energy system producing 200 quads of energy per year for about 2 billion people (Pimentel *et al.*, 2010) would provide each person with 5,000 liters of oil equivalents per year (half of America's current consumption per year but an increase for most people of the world). The appropriation of over 20% of the land area for renewable energy production will further limit the resilience of the vital ecosystem that humanity depends upon for its life support system.

House size could be reduced from the current 2,500 sq. ft. to about 1,000 sq. ft. (USCB, 2008). Heat would come from wood fuel in the northeast and north central region. About 2 ha of forest would be needed per home. This would provide about 6 tons of wood fuel per year and should be adequate for a 1,000-sq.-ft. home if well insulated. In low rainfall regions where there is little wood fuel available then wind power or photovoltaics will have to be depended on for heat. In this situation, the problem of intermediacy of energy supply can be offset by storing the heat in large hot-water tanks.

III. CONSERVATION OF SOIL NUTRIENTS

A. Critical Soil Nutrients

The three critical nutrients in crop production are nitrogen, phosphorus, and potassium. As fossil energy becomes scarce and the costs of fertilizers increase, farmers will be forced to seek alternative sources of these essential fertilizers. Nitrogen is the most vital nutrient in agricultural production and the total applied is about 12 million tons per year in the United States (USDA, 2007). The total applied in 1995 was 18 million tons, suggesting that farmers are making more effective use of nitrogen fertilizer. The 300% increase in the price of nitrogen fertilizer over the past decade has resulted in fewer nitrogen fertilizer applications and care in the use of nitrogen in crop production. The use of various agricultural technologies can conserve the use of nitrogen, phosphorus, and potassium fertilizers in crop production (Funderberg, 2001; Schmalshof, 2005).

B. Cover Crops

Conserving soil nutrients is critical in agricultural production because it reduces fertilizer nutrient demands and increases crop yields. A crucial aspect of soil nutrient conservation is the prevention of soil erosion (Troeh *et al.*, 2004). Cultivation practices that build soil organic matter and prevent the exposure of bare soil are key to preventing soil erosion (Pimentel, 2006). Cover crops help protect the exposed soil from erosion after the main crop has been harvested (Troeh *et al.*, 2004). Compared with conventional farming systems, which traditionally leave the soil bare, the use of cover crops significantly reduces soil erosion.

In addition, leguminous cover crops also add nutrients to the soil (Drinkwater *et al.*, 1998; Weinert *et al.*, 2002). For example, vetch, a legume cover crop grown during the fall after the crop is harvested and grows again in the spring months can add about 70 kg/ha of nitrogen to the soil (Pimentel *et al.*, 2005). Other studies in both the U.S. and Ghana have shown that nitrogen yields from legumes planted the season before were between 100 and 200 kg ha (Griffin *et al.*, 2000). In the organic systems at the Rodale Farms in Pennsylvania, soil nitrogen levels were 43% or significantly higher compared to only 17% for the conventional farming system (Pimentel *et al.*, 2005). Legumes as cover crops can thus provide a significant portion of the nitrogen required by most crops.

Cover crops can further aid in agriculture by collecting nearly twice as much solar energy in organic farming systems that utilized cover crops (Pimentel, 2006). Growing cover crops on land before and after a primary crop nearly doubles the quantity of solar energy harvested in the agricultural system per hectare per year. This increased solar energy capture provides additional organic matter, which improves soil quality and productivity.

C. Soil Organic Matter

Maintaining high levels of soil organic matter (SOM) is beneficial for agriculture and crucial to improving soil quality. Carter (2002) has shown aggregated SOM to have "major implications for functioning of soil in regulating air and water infiltration, conserving nutrients, and influencing soil permeability and erodibility" by improving the soil's water infiltration, structure, and reducing erosion.

Maintaining high levels of SOM is the primary focus of organic farming. On average, the amount of SOM is significantly higher in organic production systems than in conventional farming systems. Typical conventional farming systems with satisfactory soil generally have 3% to 4% SOM, whereas organic farming systems from 5% to 6% SOM (Troeh *et al.*, 2004). Soil carbon increased 28% in organic animal systems and 15% in organic legume systems, but only 9% in the conventional farming systems in the Rodale experiments (Pimentel *et al.*, 2005). The high level of SOM provides many advantages to farming systems.

High levels of SOM also provide soil with increased capacity to conserve water. Sullivan (2002) reported that about 41% of the volume of organic matter in the organic systems consisted of water, compared with only 35% in conventional systems. The large amount of soil organic matter and water present in organic farming systems is the major factor making these systems drought resistant.

In addition, 110,000 kg/ha of soil organic matter in an organic corn system can sequester 190,000 kg/ha of carbon dioxide. This is 67,000 kg/ha more carbon dioxide sequestered than in the conventional corn system, and equals the amount of carbon dioxide emitted by 10 cars that average 20 miles per gallon and travel 12,000 miles per year (Pimentel *et al.*, 2005; USCB, 2008). The added carbon sequestration benefits organic systems and have beneficial implications for reducing global warming.

IV. REDUCED PESTICIDE USE

Currently worldwide about 3 billion kg of pesticides are applied to world crops (Pimentel, 2009). However, despite this enormous amount of pesticide applied, pests (insects, weeds, and plant pathogens) destroy more than 40% of all potential crop production (Pimentel, 2009). Even in the U.S. where 500,000 kg of pesticides are applied, pests destroy 37% of all potential production or nearly the same loss as the world average (Pimentel, 2009). Worldwide after the 60% of the crops are harvested, then another group of pests in post-harvest destroy another 25% of the harvest. Thus, pests worldwide destroy about 52% of total potential food and other crops (Pimentel, 2009).

As mentioned, with organic corn and soybeans at the Rodale Farm both corn and soybeans were produced without the use of insecticides and herbicides (Pimentel *et al.*, 2005). There was, in fact, no difference between the yields in the organic and conventional production systems (Pimentel *et al.*, 2005). This confirms that although corn and soybeans in the United States use more pesticides than any other crop, both crops can be produced without the use of pesticides.

Studies have shown that pesticide use in the United States could be reduced by 50% without any reduction in crop yields (Pimentel *et al.*, 1993). This approach has been confirmed in Sweden and Indonesia. In Sweden, pesticide use has been reduced by 68% without any reduction in crop yields or cosmetic standards (Plant Science Manitoba, 2004). In Indonesia, a tropical country, the primary use of pesticides is on rice. Dr. Oka (Pimentel, 2007) has reduced pesticide use by 65% and actually increased rice yields by 12% associated with the 65% pesticide reduction.

No-till crop production associated with crops like corn, suggests there are benefits in reducing soil erosion (Pimentel *et al.*, 2008). However, no-till requires more herbicides, insecticides, mollucides, and rodenticides (Hanley, 2008). In addition, no-till requires the planting of additional corn seed because some corn seed is lost due to rotting under the exceptionally moist conditions of no-till. Also, because the nitrogen fertilizer has to be applied to the corn with corn residues on the surface of the land, some nitrogen is lost due to volitization, sheet erosion, and dentrification (Pimentel and Ali, 1998). Thus, added nitrogen fertilizer has to be applied to the no-till system (Romm, 2008).

V. CONCLUSION

The socioeconomic status of agriculture can be improved immensely and agriculture made ecologically sound by reducing energy inputs, conserving soil and water resources, and improving the nutrition of the population. People in the United States and Europe generally consume too much food per person. For example, in the United States the average caloric intake per day is nearly 3,700 kcal and for a male it should be only 2,500 kcal/day. In addition, far too many junk foods are consumed and these should be significantly reduced (Pimentel *et al.*, 2008).

Because more than 99.7% of all world food comes from the land, land and soils need to be conserved. Soil organic matter is the most valuable resource in soil. Soil organic matter should be at a level of about 6% instead of at about 3% as currently exists in the United States. The 6% improves crop productivity, conserves nutrients, and conserves water. An important addition to crop production and soil conservation is the utilization of cover crops. Cover crops help protect the soil and also, if legumes are used, this technology can add significant quantities of nitrogen to the soil.

In addition to conserving soil, water needs to be conserved. Plants require and utilize enormous amounts of water. For example, a corn crop that produced 9,000 kg/ha requires about 6 million liters of water during the growing season. On average 1 kg of plant biomass requires about 1,000 liters of water for production.

To manipulate soil, water resources, and nutrient resources required in crop production requires enormous amounts of fossil energy. Most of the fossil energy resources required and utilized are oil and natural gas. On average most foods reaching a person in the U.S. require about 10 kcal per kcal of food consumed. Of course, if the food is beef, then more than 40 kcal are required per kcal of beef protein consumed.

Overall, conserving soil, water and nutrients in food production, as well as in food processing, packaging and distribution can reduce the total energy inputs in the food system. Reducing the quantity of food consumed is also recommended where appropriate. All of these measures together can result in reducing energy inputs in the food system by about one half. This change not only conserves fossil energy, but at the same time improves the health of the people and makes agriculture ecologically sound.

REFERENCES

Bartlett, A. A. 1994. Fusion: An illusion or practical source of energy? *Clearinghouse Bulletin* **4**(1): 1–37.

Bartlett, A. A. 1998. Reflections on sustainability, population growth, and the environment – revisited. *Renewable Resources Journal* **15**(4): 6–23.

Beaumont, P. 1985. Irrigated agriculture and groundwater mining on the high plains of Texas. *Environ.* **12:** 1–11.

Berk, R., and Rothenberg, S. 2003. *Water Resource Dynamics in Asian Pacific Cities.* Department of Statistics, UCLA.

Block, G. 2004. Foods contributing to energy intake in the U.S. *J. Food Composition and Analysis* **17**(3–4): 439–447.

Carter, M. 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil function. *Agron. J.* **94**: 38–47.

Coelho, R. 2006. Some corny facts. Monday, October 23, 2006. Page 1 C. *The Ithaca Journal.* Ithaca, New York.

Covich, A. P. 1993. Water ecosystems. **In:** *Water in Crisis.* pp. 40–55. Gleick P. H., Ed. Oxford University Press, New York.

Doeoes, B. R. 1994. Environmental degradation, global food production, and risk for larger-scale migrations. *Ambio* **23**(2): 124–130.

Drinkwater, L., Wagoner, P., and Sarrantonio, M. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* **396**: 262–265.

EIA (Energy Information Agency). 2007. *World Proved Reserves of Oil and Natural Gas: Most Recent Estimates.* Washington, DC: U.S. Department of Energy.

EPA (Environmental Protection Agency). 1994. *Quality of Our Nation's Water 1994*. Washington, DC: U.S. Environmental Protection Agency.

FAO. 2004. Food balance sheets. Food and Agricultural Organization of the United Nations, Rome.

Funderburg, E. 2001. Why are nitrogen prices so high? *Pasture & Range*, April 2001. http://www.noble.org/Ag/soils/NitrogenPrices/Index.html. Accessed November 5, 2006.

Gerbens-Leenes, P. W., Nonhebela, S., and Ivens, W. P. M. F. 2002. A method to determine land requirements relating to food consumption patterns. *Agriculture, Ecosystems and the Environment* **90**(1): 47–58.

Giampietro M., and Pimentel D. 1994. Energy utilization. **In:** *Encyclopedia of Agricultural Science*, vol. 3. pp 63–76. Arntzen, C. J., and Ritter, E. M. Eds., Academic Press, San Diego, CA, USA.

Gleick, P. H. 1993. *Water in Crisis: a Guide to the World's Fresh Water Resources.* Oxford University Press, New York.

Gleick, P. H. 1996. Basic water requirements for human activities: Meeting basic needs. *Water International* **21**: 83–92.

Gleick, P. H. 2000. *The World's Water 2000-2001: The Biennial Report on Freshwater Resources.* Pacific Institute for Studies in Development, Environment and Security. Island Press, Washington, DC.

Gleick, P. H. 2009. *The World's Water 2008-2009: The Biennial Report on Freshwater Resources.* Pacific Institute for Studies in Development, Environment and Security. Island Press, Washington, DC.

Gleick, P. H., Wolff, E. L., and Chalecki, R. R. 2002. *The New Economy of Water: The Risks and Benefits of Globalization and Privatization of Freshwater.* Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA.

Griffin, T., Liebman, M. and Jemison, J. 2000. Cover crops for sweet corn production in a short-season environment. *Agron. J.* **92**: 144–151.

Hanley, P. 2008. Look at Swedish model for reduced pesticide use. *The Spirit of Agriculture*. 3 pages.

IFIA. 2008. International Fertilizer Industry Association. Statistics. http://www.fertilizer.org/ifa/ifadata/search Accessed February 12, 2009.

International Energy Annual. 1995-2007. DOE/EIA. Washington, DC: U.S. Department of Energy.

International Energy Annual. 2007. *International Energy Annual. World Energy Overview*. http://www/e/ia/doe.gov/iea/overview.html. Accessed May 15, 2008.

Kendall, H. W., and Pimentel, D. 1994. Constraints on the expansion of the global food supply. *Ambio* **23**(3): 198–205.

Kuchler, F., Tegen, A., and Harris, J. M. 2004. *Taxing Snack Foods: What to Expect for Diet and Tax Revenues*. Economic Research Service, USDA, Washington, DC. 11 pages.

Lal, R. 1989. Land degradation and its impact on food and other resources. **In**: *Resources.* pp. 85–140. Pimentel, D., Ed., Academic Press, San Diego.

Lal, R. 1998. Soil erosion impact on agronomic productivity and environment quality. *Crit. Rev. Plant Sci.* **17**(4): 319–464.

Leach, G. 1995. *Global Land and Food in the 21st Century.* International Institute for Environmental Technology and Management, Stockholm.

McMichael, A. J. 1993. *Planetary Overload: Global Environmental Change and the Health of the Human Species.* Cambridge University Press, Cambridge.

Miller, H. I. 2008. The United Nation's unscientific war on biotechnology. Insightful analysis on world events. *World Politics Review*.

Murray, C. L., and Lopez, A. D. 1996. *The Global Burden of Disease: A Comprehensive Assessment of Mortality and Disability from Diseases, Injuries, and Risk Factors in 1990 and Projected to 2020.* Harvard School of Public Health, Cambridge, MA.

Myers, N. 1990. The Non-timber Values of Tropical Forests. Forestry for Sustainable Development Program, University of Minnesota, November, 1990. Report 10.

NAS. 2003. *Frontiers in Agricultural Research: Food, Health, Environment and Communities.* National Academy of Sciences. National Academy of Sciences Press: Washington, DC.

Nash, L. 1993. Water quality and health. **In**: *Water in Crisis: A Guide to the World's Fresh Water Resources.* pp. 25–39. Gleick, P., Ed., Oxford University Press, Oxford.

Nesheim, M. C. 1993. Human nutrition needs and parasitic infections. **In**: *Parasitology: Human Nutrition and Parasitic Infection*. pp. s7–s18. Crompton, D., Ed., Cambridge University Press, Cambridge.

NGS. 1995. *Water: A Story of Hope.* National Geographic Society, Washington, DC.

O'Brien, D. M., Rogers, D. H., Lamm, F. R., and Clark, G. A. 1998. An economic comparison of subsurface drip and center pivot irrigation systems. Soil and Water Division of ASAE 97-2072, pp.391–398. http://www.oznet.ksu.edu/sdi/Reports/1998/EconSDICP.pdf. Accessed December 12, 2008.

Parrington, J. R., Zoller, W. H., and Aras, N. K. 1983. Asian dust: Seasonal transport to the Hawaiian Islands. *Science* **246**: 195–197.

Pimentel, D. 2006. Soil erosion: A food and environmental threat. *Environment, Development and Sustainability* **8**: 119–137.

Pimentel, D. 2007. Area-wide pest management: environmental, economic and food issues. **In**: *Area-wide Control of Insect Pests: From Research to Field Implementation.* pp. 35–47. Vreysen, M. J. B., Robinson, A. S. and Hendrichs, J. , Eds., International Atomic Energy Agency. Springer, Dordrecht, The Netherlands.

Pimentel, D. 2008. Renewable and solar energy technologies: energy and environmental issues. **In**: *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks.* pp. 1–17. Pimentel, D., Ed., Springer: Dordrecht, The Netherlands.

Pimentel, D. 2009. Reducing pesticide use by 50%. Manuscript form.

Pimentel, D., and Ali, M. S. 1998. An economic and environmental assessment of herbicide-resistant and insect/pest-resistant crops. *Indian J. Appl. Econ.* **7**(2): 241–252.

Pimentel, D., Bailey, O., Kim, P., Mullaney, E., Calabrese, J. Walman, L., Nelson, F., and Yao, X. 1999. Will limits of the Earth's resources control human numbers? *Environment, Development, and Sustainability* **1**(1): 19–39.

Pimentel, D. Cooperstein, S., Randell, H., Filiberto, D., Sorrentino, S., Kaye, B., Yagi, C.J., Brian, J., O'Hern, J., Habas, A., and Weistein, C. 2007. Ecology of increasing diseases: Population growth and environmental degradation. *Human Ecol.* **35**(6): 653–668.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurtz, D., McNair, M., Crist, S., Spritz, L., Fitton, L., Saffouri, R., and Blair, R. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* **267**: 1117–1123.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., and Seidel, R. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. *Bioscience* **55** (7): 573–582.

Pimentel, D., McLaughlin, L., Zepp, A., Lakitan, B., Kraus, T., Kleinman, P., Vancini, F., Roach, W.J., Grapp, E., Keeton, W. S., and Selig, G. 1993. Environmental and economic effects of reducing pesticide use in agriculture. *Agriculture, Ecosystems and Environment* **46**(1-4): 273–288.

Pimentel, D., and Pimentel, M. 2008. *Food, Energy and Society. 3rd Edition.* CRC Press (Taylor and Francis Group), Boca Raton, FL.

Pimentel, D., Pleasant, A., Barron, J., Gaudioso, J., Pollock, N., Chae, E., Kim, Y., Lassiter, A., Schiavoni, C., Jackson, A., Lee, M., and Eaton, A. 2004. U.S. Energy conservation and efficiency: Benefits and costs. *Environment, Development and Sustainability* **6**: 279–305.

Pimentel, D., and Wen, D. 2004. China and the world: population, food and resource scarcity. **In**: *Dare to Dream: Vision of 2050 Agriculture in China.* pp. 103–116. Tso, T. C. and He Kang, Eds., China Agricultural University Press, Beijing.

Pimentel, D., Westra, L., and Noss, R.F. 2000. *Ecological Integrity.* Island Press, Washington, DC.

Pimentel, D., Whitecraft, M., Scott, Z., Zhao, L., Satkiewicz, P., Scott, T., Phillips, J., Szimak, D., Singh, G., Gonzalez, D., and Moe, T.-L. 2010. Will limited land, water, and energy control human population numbers in the future? *Human Ecology* **38**(5): 599–611.

Pimentel, D., Williamson, S., Alexander, C. E., Gonzalez-Pagan, O., Kontak, C., and Mulkey, S.E. 2008. Reducing energy inputs in the U.S. food system. *Human Ecol.* **36** (4): 459–471.

Pimentel, D., Wilson, C., McCullum, C., Huang, R., Dwen, P., Flack, J., Tran, Q., Saltman, T., and Cliff, B. 1997. Economic and environmental benefits of biodiversity. *BioScience* **47** (11): 747–757.

Plant Science, Manitoba. 2004. Pesticide free peas in no-till production. Natural Systems Agriculture. Department of Plant Science. University of Manitoba. http://www.umanitoba.ca/outreach/naturalagriculture/profiles/peas/peas.html Accessed on April 13, 2009.

Postel, S. 1996. *Dividing the Waters: Food Security, Ecosystem Health, and the New Politics of Scarcity*. Vol. 132. Worldwatch Institute: Washington, DC.

Postel, S. 1997. *Last Oasis: Facing Water Scarcity.* W.W. Norton, New York.

PRB. 1996. World Population Data Sheet. Population Reference Bureau, Washington, DC.

PRB. 2008. World Population Datasheet. Population Reference Bureau, Washington, DC.

Rehydration project. 2007. 10 Basic facts on child deaths. October 29, 2007. http://rehydrate.org/facts/ten-facts.htm Accessed on April 16, 2009.

Romm, J. 2008. The truth about no-till farming. http://gristmill.grist.org/story/2008/5/21/15367/8993. Accessed on December 12, 2008.

Schmalshof, T. 2005. Testimony. National corn growers association. Before the House subcommittees on energy and mineral resources. May 19, 2005, Washington, DC.

Schwarz, M. 1995. *Soilless Culture Management.* Springer-Verlag, New York.

Sullivan, P. 2002. Drought resistant soil. Fayetteville (AR): Appropriate Technology Transfer for Rural Areas. www.attra.org/attra.pub/pub/drought.pdf. Accessed April 22, 2005.

Tolba, M. K. 1989. Our biological heritage under siege. *Bioscience* **39**: 725–728.

Troeh, F., Hobbs, J., and Donahue, R. L. 2004. *Soil and Water Conservation for Productivity and Environmental Protection. 4th ed*. Prentice Hall, New Jersey.

UNEP. 1991. *Freshwater Pollution. Nairobi.* Global Environment Monitoring System. United Nations Environmental Programme.

UNESCO. 2001. *Securing the Food Supply.* World Water Assessment Programme. United Nations Education Scientific and Cultural Organization (Paris).

UNFPA. 1991. *Population and the Environment: The Challenges Ahead.* United Nations Fund for Population Activities. United Nations Fund for Population Activities: New York.

USCB. 2007. *Statistical Abstracts of the United States*. United States Census Bureau: Washington, DC.

USCB. 2008. *Statistical Abstracts of the United States*. United States Census Bureau: Washington, DC.

USDA. 1976. *Nutritive Value of American Foods.* Agricultural Handbook No. 456. U.S. Department of Agriculture. Agricultural Research Service, Washington, DC.

USDA. 1996. *Agricultural Statistics.* U.S. Department of Agriculture, Washington, DC.

USDA. 2007. ERS/USDA Data: Major Land Uses. United States Department of Agriculture. http://www.ers.usda.gov/Data/MajorLandUses/ *on* Accessed January 28, 2009.

Valentine, J. 2006. Soft drinks: America's other drinking problem. http://www.westonaprice.org/modernfood/soft.html. Accessed April 2, 2007.

Weinert, T., Pan, W., Moneymaker, M., Santo, G., and Stevens, R. 2002. Nitrogen recycling by nonleguminous winter cover crops to reduce leaching in potato rotation. *Agronomy Journal* **94**: 365–372.

Wen, D., and Pimentel, D. 1992. Ecological resource management to achieve a productive, sustainable agricultural system in northeast China. *Ecosystems and Environment* **41**: 215 – 230.

WHO. 1992. *Our Planet, Our Health: Report of the WHO Commission on Health and Environment*. World Health Organization: Geneva.

WHO. 1993. Global health situation. World Health Organization. *Weekly Epidemiological Record* **68**: 43–44.

WHO. 2005. *Malnutrition Worldwide*. World Health Organization.

www.mikeschoice.com/reports/malnutrition_worldwide.html Accessed on 9 February 2009.

WRI. 1991. *World Resources, 1991-1992*. World Resources Institute: Washington, DC.

WRI. 1996. *World Resources, 1996-97.* World Resources Institute: Washington, DC.

Youngquist, W. 1997. *GeoDestinies: The Inevitable Control of Earth Resources Over Nations and Individuals.* National Book Company, Portland, OR.

Critical Reviews in Plant Sciences, 30:45–63, 2011

ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554352

Food Security and Fossil Energy Dependence: An International Comparison of the Use of Fossil Energy in Agriculture (1991-2003)

Nancy Arizpe,[1] **Mario Giampietro,**[2] **and Jesus Ramos-Martin**[1,3]
[1]*Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, Edifici C, 08193 Bellaterra (Cerdanyola), Spain*
[2]*ICREA Research Professor at the Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, 08193 Bellaterra (Cerdanyola), Spain*
[3]*Departament d'Economia i d'Història Econòmica, Universitat Autònoma de Barcelona, Edifici B, 08193, Bellaterra (Cerdanyola), Spain*

Table of Contents

Address correspondence to Mario Giampietro, ICREA Research Professor at the Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona, 08193 Bellaterra (Cerdanyola), Spain. E-mail: Mario.Giampietro@uab.cat.

Referee: Prof. David Pimentel, Cornell University, 5126 Comstock Hall, Ithaca, NY 14853–0901, USA

The serious food crisis in 2007 has reinstated the issue of food security. In particular, it evokes an old set of questions associated with the sustainability of an adequate food supply: are we facing a systemic shortage of arable land for food production? How serious is the oil dependence of food security in relation to peak oil (the point in time when the maximum rate of global oil extraction is reached)? To answer these questions one has to study the role of technical inputs in agricultural production, especially those inputs generated from fossil energy (how much fossil energy is used? for which inputs? in relation to which tasks?). This paper provides a synchronic comparison—e.g., comparing the use of technical inputs in 21 countries belonging to different typologies, at a given point in time—and a diachronic comparison, e.g., comparing the use of technical inputs in the same sample of 21 countries, over a time window of 12 years (1991–2003). The results confirm the conclusions of previous studies and include the following: (i) current pattern of inputs use reflects the existence of different typologies of constraints in different typologies of countries. Wealthier countries must have a very high productivity of labor, whereas poor and crowded countries must have a very high productivity of land. Different technical inputs are used for different purposes: irrigation and fertilizers are used to boost yield per hectare; machinery and infrastructures to boost the productivity of labor; and (ii) when looking at the changes over the period of 12 years we see a constant and worrisome trend. The pattern of energy use in agriculture associated with the paradigm of industrial agriculture (High External Input Agriculture) has been simply amplified, by doing more of the same, with only minor adjustments in special countries. For those looking for a major transition toward a different pattern of production more focused on rural development, ecological compatibility and quality food, this is a reason for concern.

Keywords Fossil energy in agriculture, international comparison, energy output-input, demographic pressure, bio-economic pressure, energy analysis of food production, agricultural development

I. INTRODUCTION

In the five years previous to mid 2008 the prices of basic food commodities doubled or tripled. For instance, the cereals FAO price index went up from 95 in 2002 to 167 in 2007 (FAO, 2009). This generated a serious food crisis in 2007, which was experienced worldwide (both in developed and developing world) and primed food riots in many cities of developing countries (Krugman, 2008). This food crisis can be explained by a combination of the following factors: (i) increase in food demand due to world population growth; (ii) changes in dietary habits, with an increase in the consumption of animal products, which entail a double conversion of grains used to feed animals (Pingali, 2006); (iii) the occurrence of unfortunate events (such as a couple of poor years of production); and (iv) the increasing demand of grains for agro-biofuels (IMF, 2007; The Guardian, 2008; World Bank, 2008; Giampietro and Mayumi, 2009). The food crisis was harder in developing countries, where food's share in household spending is higher (IMF, 2007). Are we in the presence of a systemic change in the existing balance between demand and supply? In the affirmative, this would imply that the issue of food security, interpreted as the ability of producing enough food supply over a limited amount of available land—which is shrinking with demographic growth—will get more and more relevant at the world level.

In relation to this point, Ramonet (2009) reported that in the last years more than 8 million hectares of agricultural land have already been purchased worldwide by countries with a limited endowment of arable land per capita such as South Korea, China, Saudi Arabia, and Japan. These figures change according to the source. GRAIN (2008) called this process "land grabbing" and stated that to date more than 40 million acres have changed hands or were under negotiation—20 million of which were in Africa alone, with the side effect of reducing the number of small scale farmers and adding more pressure to water resources. Williams (2009), reporting on an UN event to try to prevent this trend in Africa, quoted David Hallam, deputy director of the trade and markets division at the UN's Food and Agriculture Organization (FAO) saying that "in the worst cases it's fair to say we are looking at neo-colonialism."

When dealing with the issue of food security and sustainability of agriculture, it is essential to focus on the constraint that the requirement of land, soil, water and other natural resources entails on the possibility of generating an adequate supply of food (Pimentel and Giampietro, 1994a). In fact, the severity of this constraint determines the amount of technical inputs that have to be used in agricultural production (or that should be used to get a certain output), which in turn affect the ecological impact of this production. Therefore, it is important to visualize the big picture of existing trends of technical progress in agriculture at the world level, in order to be able to contextualize the discussion of alternative techniques of agricultural production. When talking of the use of technical inputs in agriculture, it is well known that the revolution in the yields achieved in the last century can only be explained by the massive injections of fossil energy associated with modern techniques of agricultural production (Cottrell, 1955; Gever *et al*., 1991; Leach, 1976; Odum, 1971; Pimentel and Pimentel, 1979; Smil, 1988, 1991, 2001; Steinhart and Steinhart, 1974). The success of this solution has been extraordinary: "In the past century, the world population has tripled from 2 billion at the beginning of the twentieth century to more than 6 billion at present. It is most impressive to say that the increase in the productivity of agriculture was able to meet the increase the demand for food by this increased population, at the same time that land per capita was proportionally shrinking. Moreover, agriculture did not only meet the growing food demand due to population growth, but it also succeeded to match the demand of food of more people consuming much more per capita. In fact, at present, the grain consumption per capita in developed countries is around 700 kg of grain per year with peaks up to 1,000 kg per year—when including the indirect consumption in the food system for animal production, beer production, and other industrial food products" (Giampietro and Mayumi, 2009). But this extraordinary success implies a risk, an increasing dependence of food security on fossil energy: "the survival of peasants in the rice fields of Hunan or Guadong—with their timeless clod-breaking hoes, docile buffaloes, and rice-cutting sickles—is now much more dependent on fossil fuels and modern chemical syntheses than the physical well-being of American city dwellers sustained by Iowa and Nebraska farmers cultivating sprawling grain fields with giant tractors. These farmers inject ammonia into soil to maximize operating profits and to grow enough feed for extraordinarily meaty diets; but half of all peasants in Southern China are alive because of the urea cast or ladled onto tiny fields—and very few of their children could be born and survive without spreading more of it in the years and decades ahead." (Smil, 1991, p. 593).

For this reason analyzing the dependence of food production on fossil energy has become a very important topic (Stout, 1991, 1992; Pimentel and Giampietro, 1994b; Giampietro, 2002; Pimentel and Pimentel, 1996; Smil, 1988, 1991, 2001).

Ten years ago, in another special issue of Critical Review in Plant Science dedicated to the sustainability of agriculture (Paoletti *et al*., 1999), one of the papers was dedicated to an international comparison of the use of fossil energy in agriculture (Giampietro *et al*., 1999). The goal was to study the different mixes of technical inputs used in different typologies of countries, over a significant sample of world countries. In this paper, we repeat, 10 years after, the same type of analysis with the goal of studying the evolution of the pattern of use of technical inputs in different typologies of countries. What happened in relation to this issue in the last ten years? Are we reducing the dependence of our food security on oil? These questions are extremely relevant since the era of cheap energy seems to be over and for good. The chosen sample includes countries at different levels of density of population (net exporters vs. net importers of food) and at different levels of economic development (developed vs. developing countries). The comparison over the chosen sample of countries refers to the years 1991 and 2003.

Looking at the future, peak oil could imply a possible reduction in the current heavy use of fossil energy inputs to agriculture. This reduction may very well be accompanied by an increase in labour inputs and a reduction of transport. This combination of changes could eventually lead to food production being devoted primarily to local consumption. This scenario seen by some authors as almost unavoidable—"Fossil fuel depletion almost ensures that this *will* happen" (Heinberg, 2007)—will represent a disaster for the growing mass of urban poor in many developing countries. To this regard, it should be noted that in 2007 more than 50% of human population was urban (UNFPA, 2008). This explains why, a better understanding of the link between the use of the different technical inputs and food production is essential for discussing future scenarios of food security. In particular, in order to develop alternative methods of production, it is important to compare the use of fossil energy (how much fossil energy? for which inputs? in relation to which tasks?) in the agricultural sector of different countries.

II. MATERIALS AND METHODS

A. The Sample

The selected sample is the same as in the previous CRPS paper of 1999, it includes 21 countries representing America, Europe, Asia, Africa and Australia. The chosen sample of countries covers different combinations of economic development (measured by GDP) and population density (measured by availability of arable land per capita).

- *Developed countries:* United States, Canada, and Australia (important food exporters with low population density), France (net food exporter within EU), the Netherlands, Italy, Germany, Spain, United Kingdom and Japan (net food importers).
- *Countries with an intermediate GDP:* Argentina (with abundant arable land), Mexico, and Costa Rica
- *Countries with a low GDP:* P.R. China, Bangladesh, India, and Egypt (all with little arable land per capita); Zimbabwe (net food exporter), Uganda, Burundi, Ghana.

B. The Theoretical Framework of the Analysis

The overall value of the output/input energy ratio of agricultural production, refers to two distinct typologies of energy flows: (A) the energy output, which is food energy produced in the crops; and (B) the energy input, which is the fossil energy embodied in the technical inputs used in agricultural production. These two flows are not directly related to each other in terms of their relative value to society. When analyzing the energetic efficiency of agricultural production we face a paradox (Giampietro *et al*., 1999): "In the last decades technical development in agriculture has led to a reduced efficiency of energy use, when assessed by the output/input energy ratio in agricultural production (Pimentel and Pimentel, 1979; Pimentel *et al*. 1990) together with a diminished use of biodiversity in food production (Altieri *et al*., 1987; Wilson, 1988)." To explain this paradox it is important to understand that beside the energetic efficiency of the agronomic production there are a lot of other relevant criteria of performance determined by the strong conditioning that the socioeconomic context imposes on the technical choices made at the farming system level (Giampietro *et al*., 1994; Giampietro, 1997a, 1997b, 2003; Conforti and Giampietro, 1997). In particular explaining the evolution in the pattern of use of technical inputs in agricultural systems requires establishing a relation between

1. *changes taking place in the socio-economic context of the farm*. For this task we use in this analysis two indicators: demographic and bio-economic pressure; and
2. *changes taking place within the farm*. For this task we check in this analysis the changes taking place in the pattern of use of technical inputs—the mix of irrigation, fertilizer, pesticides, and machinery.

The basic rationale behind this analysis is that technical progress of agriculture has been driven by two objectives (Hayami and Ruttan, 1985; Giampietro, 1997b): (1) boost the productivity of labor in the agricultural sector; and (2) boost the productivity of land in production. Therefore, technical progress (coupled to economic growth) has implied a continuous increase in the injection of technical inputs into the process of agricultural production in order to increase the net supply of: (i) food per hectare (in response to the growing Demographic Pressure); and (ii) food per hour of labor in the agricultural sector (in response to the growing Bio-Economic Pressure).

As explained by Giampietro and Mayumi (2009) "The priority given to these two objectives, under the alleged label of "technological progress in agriculture," has been driven by two crucial transformations that took place in developed societies in previous decades:

1. A dramatic socioeconomic re-adjustment of the profile of investment of human time, labor and capital over the different economic sectors in industrial and post-industrial societies. This transformation required the progressive elimination of farmers to free labor for the work force in other economic sectors, initially the industrial sector and later the service sector;
2. The demographic explosion that took place, first in the developed world and later everywhere, linked to the phenomenon characterized as 'globalization of the economy'. This explosion did, and still does require boosting the yields on land in production due to the progressive reduction of the available arable land per capita."

To study the different effects of these two pressures on the technical development of agriculture in the countries included in the sample in this study we assume the following relations:

(i) the performance in terms of "land productivity"—the level of crop production per hectare (MJ/ha)—is correlated to differences in "demographic pressure." An increase in demographic pressure is defined as the reduction in available cropland per capita, associated with population growth. An increase in Demographic Pressure implies the need to boost the yields per hectare, to remain self-sufficient in food production;
(ii) the performance in terms of "labor productivity"—the level of crop production per hour of work allocated to agriculture (MJ/hour)—is correlated to differences in "bio-economic pressure."

Increase in bio-economic pressure (BEP) is defined as the reduction of the fraction of farmers in the work force, associated with economic growth. An increase in BEP makes it necessary to produce more crops per hour of work in agriculture, to remain self-sufficient in food production. The main factor determining the increase in BEP is economic growth in the economy, rather than any "biological" factor. Using the jargon used in conventional development economics, the process of declining active population in agriculture is explained as follows. Labor productivity goes up in agriculture because of technical improvement (nothing is said about energy input), while production cannot increase at the same pace of productivity because of low income-elasticity of demand for agricultural products as a whole (Engel's Law). Therefore, economic growth implies that agriculture tends to expel active population.

This assumption of an existing relation between: (i) agricultural land productivity and Demographic Pressure (DP); and (ii) agricultural labor productivity and Bio-Economic Pressure ; was confirmed by the empirical analysis discussed in two previous papers (Giampietro, 1997b; Conforti and Giampietro, 1997).

In this paper we characterize changes in relation to these concepts as follows:

#1. Demographic Pressure (DP) and Bio-Economic Pressure (BEP)—seen as drivers of technical progress in agriculture

Demographic Pressure—to quantify the demographic pressure on agricultural production we calculate the level of agricultural productivity imposed by demographic pressure. This is defined as the productivity of land (yield of food energy per hectare) that would be needed to obtain a situation of complete food self-sufficiency in society (Giampietro, 1997b; Giampietro *et al*., 1999). This threshold level can be calculated from:

- The aggregate requirement of food in society (considering the food system under analysis as closed), which is determined by the population size of society, food consumption pattern, and post-harvest losses. This information is available by consulting FAO Food Balance Sheet (total consumption of the population). In this study we consider the energetic value of plant crops (consumed directly and indirectly), to account for differences in the quality of the diet, determined by the amount of animal products, requiring a double conversion of plant calories into animal product calories—for more see Giampietro (1997b).
- The land available for food production, which depends on availability of arable land, characteristics of this arable land, and alternative land uses (dependent on population size and technological development). This information is available from FAO statistics (arable land and permanent crops). High demographic pressure in society will invariably favor farming techniques and crop mixes that yield a high food production per unit of area (Boserup, 1981; Hayami and Ruttan, 1985). This implies that the higher is the demographic pressure —proxy: population divided by colonized land—the higher can be expected to be the productivity of land—proxy: the food energy yields of cultivated crops.

Bio-Economic Pressure in agriculture—the bio-economic pressure determined by economic growth can be described as the need of reaching high level of labor productivity in specialized compartments of the economy, which are in charge of producing the supply of critical input consumed by society (Giampietro and Mayumi, 2000, 2009). In relation to food security, the bioeconomic pressure indicates the level of productivity of labor, which should be achieved per hour of labor in agriculture, to obtain a situation of complete food self-sufficiency in society. For example, in 1999 the entire amount of food consumed per capita in a year by a U.S. citizen (the United States is among the countries with the highest consumption of food items per capita) was produced using only 17 hours of work in the U.S. agricultural sector (Giampietro, 2002). In general, quantitative indicators of Bio-Economic Pressure correlate well with all the other indicators of development such as Gross Domestic Product or commercial energy consumption per capita (Pastore *et al.*, 2000).

In this paper, we define Bio-Economic Pressure in Agriculture as the level of agricultural labor productivity (yield of food energy per hour of labor in the agricultural sector) that would be required to produce the food consumed in a society. In this calculation we consider the same overall energetic requirement of food calculated for determining the demographic pressure. That is, we consider the society's food system as closed. Then, we divide the aggregate requirement of primary food energy of the whole society in a year by the labor time available in a year in the agricultural sector. The latter depends on the size of the labor force, the unemployment rate, the fraction of the labor force absorbed by the nonagricultural sectors, and the average work load (Giampietro, 1997b). A high Bio-Economic Pressure in society favors farming techniques and crop mixes that yield a high food production per hour of work (Hayami and Ruttan, 1985; Giampietro, 1997b). That is, the higher is the Bio-Economic Pressure in agriculture—proxy: total primary food energy consumed by the society (total food consumption) per hour of work in the agricultural sector (numbers of active workers in agriculture × 2000 hours/year)—the higher can be expected to be the productivity of labor of farmers—proxy: the amount of food energy produced per hour of work in agriculture.

As a matter of fact, imports and exports make it possible for modern societies to have a certain level of independence between: (a) the level of internal consumption of food both per hour of work in agriculture and per hectare of land in production in agriculture; and (b) the level of internal production of food both per hour of work in agriculture and per hectare of land in production in agriculture. However, as proved by the empirical analysis, these two distinct types of pressure play an important role in shaping the use of technical inputs across world countries.

#2. The use of technical inputs in relation to these two different pressures: (i) irrigation and fertilizers are required to deal with the demographic pressure; whereas (ii) machinery is required to deal with the Bio-Economic Pressure.

Previous studies on the use of technical inputs in agriculture (Giampietro 1997b; 2002; Conforti and Giampietro, 1997; Giampietro *et al.*, 1999) provided the following explanations in relation to the mix of inputs used in different typologies of agricultural production:

* Irrigation and fertilizers are used more in crowded countries, independently of the level of economic growth, since they respond to the intensity of the demographic pressure—they boost the production per hectare of land.

* Machinery is used, but in special niches, only in developed countries, independently of the level of demographic pressure, since it responds to the intensity of the Bio-Economic Pressure—they boost the production per hour of labor.

In this study we will double-check these assumptions not only by providing a synchronic comparison, e.g., comparing the use of inputs of 21 countries belonging to different typologies at a given point in time. We will also provide a diachronic comparison, e.g., the comparison over the same sample of 21 countries performed at two points in time 1991 and 2003, that is, over a time window of 12 years.

C. Data Source and Conversion Factors

The quantitative assessments given in this study are based on:

1. The Data-Set Taken From FAO Agricultural Statistics

Databases for world agricultural production are available at FAO web site (http://www.fao.org/corp/statistics). We selected data referring to 1991 and 2003. This database covers different aspects of agricultural production: (1) means of production, e.g., various technological inputs used in production (excluding data on pesticide use), (2) food balance sheets—accounting of production, imports, exports and end uses of various products, as well as composition of diet and energetic value of each item, per each social system considered; (3) data on agricultural production, and (4) data on population and land use. Data on pesticides have been estimated using data from literature. Assessments of pesticide consumption have been re-arranged starting from the estimates of Pimentel (1997) to fit FAO system of aggregation.

The data used in this study are reported in Table 1.

2. The Set of Energy Conversion Factors Taken From an Overview of the Available Data in the Specialized Literature

Energy conversion factors tend to apply generalized values, but at the same time to reflect peculiar characteristics of various socio-economic contexts in which agricultural production occurs (e.g., reflecting the system of aggregation provided by FAO statistics).

The conversion factors used to assess the amount of embodied fossil energy are slightly different from those used in the original study of Giampietro *et al.*, 1999, since some data have been updated. For this reason, the original data set used in the CRPS paper of Giampietro *et al.* (1999) has been recalculated using this set of conversion factors to obtain a better comparability of the two assessments presented in this paper referring to 1991 and 2003.

TABLE 1

Relevant characteristics of selected countries.

	Technical Inputs																							
	Gross Foot Consumption (PJ/Year)		Gross Food Production (PJ/Year)		Land in Production (MHa)		Work in Production (MHours)		Irrigation (1000sHa)		Harversters-Threshers		Tractors		Nitrogenous Fert. Consumption Tonnes		Phosphate Fertilizers Tonnes		Potash Fertilizers Tonnes		Pesticides Tonnes	
	91	2003	91	2003	91	2003	91	2003	91	2002	91	2003	91	2003	91	2002	91	2002	91	2002	92	2000
Argentina	175	211	407	660	27	29	2962	2916	1560	1561	48800	50000	274034	299620	95700	432628	54500	283300	17100	23598	—	—
Australia	125	210	318	615	46	48	924	878	4	4	56600	56500	316000	315000	462300	972300	680200	1077290	142100	230000	119654	—
Bangladesh	376	523	325	455	9	8	70414	78932	3027	4597	0	0	5250	5530	705600	1049900	216600	222300	82200	151400	2906	6340
Burundi	20	20	20	19	1	3	5616	6468	72	74	2	2	165	170	1000	852	1000	711	100	976	186	218
Canada	347	492	689	683	52	52	966	724	720	785	152114	115800	734149	732600	1253287	1629763	592300	637910	327497	346082	58936	—
China	5844	6481	5586	6218	131	155	993050	1021146	48384	54937	43996	362200	795713	995421	19970500	25430147	7284300	9924054	2404300	4250465	208	37
Costa Rica	16	23	16	22	1	1	618	652	78	108	1180	1190	6500	7000	62400	52068	16000	33743	38000	65751	—	40120
Egypt	360	501	224	320	3	3	15340	17070	2643	3400	2260	2325	59000	89700	775000	1068923	150000	142179	38400	57701	10954	—
France	487	542	890	836	19	20	2606	1562	2100	2600	122300	91000	1410000	1264000	2569000	2279000	1255000	729000	1741000	960000	85249	97490
Germany	581	706	639	688	12	12	3044	1762	482	485	141200	135000	1500000	944000	1720000	1787654	519000	327000	729658	479673	55415	57788
Ghana	75	122	69	112	4	6	8670	11762	9	11	130	19	4050	3600	7000	14170	200	8590	800	8270	—	164
India	3150	4013	3095	3790	169	170	466048	547030	47430	57198	3000	4200	1063012	2528122	8046272	10470810	3321213	4004779	1360600	1646993	141539	91487
Italy	182	425	171	302	12	11	4024	2316	2710	2750	47715	37500	1455811	1680000	906720	785314	661970	372026	418000	275302	170169	150450
Japan	736	697	263	239	5	5	8878	4618	2825	2607	1169000	1042000	1966000	2028000	576000	463000	696000	482000	480000	339000	—	—
Mexico	538	797	432	563	26	27	17106	16968	5800	6320	19000	22500	317313	324890	1155200	1176400	379900	349900	84300	185600	—	—
Netherlands	152	198	103	115	1	1	616	454	557	565	5560	5600	182000	149500	391759	284000	75000	52000	94000	66000	—	—
Spain	346	513	338	409	20	19	3656	2330	3388	3780	48821	50454	755743	943653	862156	802500	501655	601300	381382	488300	31839	35700
Uganda	83	123	81	115	7	7	15238	7312000	9	9	15	15	4600	4700	500	4330	300	2698	400	2278	144	
UK	369	428	355	350	7	6	1200	1002	165	170	48000	47000	500000	500000	1365000	1142000	365000	283000	441000	376000	59448	63093
US	3146	3838	3769	4764	188	176	7156	5696	20900	22500	663000	662000	4541725	4760000	10383900	10878330	3826400	3874960	4573700	4545159	408686	—
Zimbabwe	32	39	34	29	3	1	6546	7154	100	117	833	800	18000	240	89822	60000	43200	30000	31100	20000	5222	—

Source: Data from FAOSTAT and WRI.

(1) Machinery—to assess energy equivalent of machinery from FAO statistics we adopted basic conversion factors suggested by Stout (1991), since they refer directly to FAO system of accounting. A standard weight of 15 Metric Tons (MT) per piece (both for Tractors and for Harvester and Thresher) for the United States, Canada, and Australia; a common value of 8 MT for pieces in Argentina and Europe; a common value of 6 MT for pieces in Africa and Asia. To the resulting machinery weight Stout suggests an energy equivalent of 143.2 GJ/Metric Ton of machinery. This value (which includes maintenance, spare parts and repairs) is quite high, but it has to be discounted for the life span of machinery. It is the selection of the useful life, which will define, in ultimate analysis, the energy equivalent of a metric ton of machinery. Looking at other assessments, made following a different logic, it is possible to find in literature values between 60 MJ/kg for H&T and 80 MJ/kg for tractors, but only for the making of the machinery. The range of 100–200 MJ/kg found in Leach analysis (Leach, 1976) includes also the depreciation and repair. Pimentel and Pimentel (1996) suggest an "overhead" of 25–30% for maintenance and repairing to be added to the energy cost of making. In general a 10-year life-span is applied to these assessments. The original value of 143.2 GJ/Metric Ton of machinery suggested by Stout can be imagined for a longer life-span than 10 years (the higher the cost of maintenance and spare parts the larger should be the life span). Depending on different types of machinery the range can be 12–15 years. Therefore, in this assessment a flat discount of 14 years has been applied to the tons of machinery, providing an energy equivalent of 10 GJ/MT/year.

(2) Oil consumption per piece of machinery—conversion factors from Stout (1991). Again, these factors refer directly to data found in FAO statistics. The estimates of consumption of fuel per piece are the following: 5 MT/year for the United States, Canada, and Australia; 3.5 MT/year for Argentina and Europe; 3 MT/year for Africa and Asia. The energy equivalent suggested by Stout is quite low (42.2 GJ/MT of fuel – typical for gasoline, without considering the cost of making and handling it). A quite conservative value of 45 GJ/MT as average fossil energy cost of "fuel" has been adopted.

(3) Fertilizers—conversion factors from Hesel (1992), within the Encyclopedia edited by Stout (1992). These assessments include also the packaging, transportation and handling of the fertilizers to the shop. Values are:

- For Nitrogen, 78.06 MJ/kg—this is higher than the average value of 60–63 MJ/kg for production (Smil, 1987; Pimentel and Pimentel, 1996) and lower than the value estimated for production of Nitrogen in inefficient plants powered by coal (e.g., in China), that can reach the 85 MJ/kg reported by Smil (1987).
- For Phosphorous, 17.39 MJ/kg—this is higher than the standard value of 12.5 MJ/kg reported for the process of production (Pimentel and Pimentel, 1996). But still in the range reported by various authors: 10–25 MJ/kg by Smil (1987), 12.5–26.0 MJ/kg by Pimentel and Pimentel (1996). The packaging and the handling can explain the movement toward the upper value in the range.
- For Potassium, 13,69 MJ/kg—also in this case the value is quite higher than the standard value of 6.7 MJ/kg reported for production. Ranges are 4–9 MJ/kg given by Smil (1987) and 6.5–10.5 MJ/kg given by Pimentel and Pimentel (1996). Clearly, the energy related to the packaging and handling, in this case influences in a more evident way the increase in the overall cost per kg.

(4)Irrigation—conversion factors suggested by Stout (1991) are 8.37 GJ/ha/year for Argentina, Europe, Canada, the United States, and Asia; and 9.62 GJ/ha/year for Africa and Australia. These values refer to full fossil energy based irrigation. However, when looking at FAO statistics on irrigation one can assume that only a 50% of it is machine irrigated. So that this conversion factor has been applied only to 50% of the area indicated as irrigated (but in Australia).

(5) Pesticides—a flat value of 420 MJ/kg has been used for both developed and developing countries. This includes packaging and handling (Hesel, 1992). Values in literature vary between 293 MJ/kg for low quality pesticides in developing countries to 400 MJ/kg in developed countries (without including packaging and handling).

(6) Other energy inputs—at the agricultural level there are other technical inputs which are required for primary production. For example, infrastructures (commercial buildings, fences), electricity for on farm operations (e.g., drying crops), energy for heating, embodied energy in vehicles and fuels used for transportation. For this reason a flat 5% of the sum of previous energy inputs has been adopted in this analysis. This has been applied only to agricultural production in developed countries.

III. THE RESULTS OF THE STUDY

A. The effect of changes in Demographic Pressure and Bio-Economic Pressure

In relation to the 21 countries included in the sample we report in Table 2:

(i) the actual *land productivity* (density of the internal supply of food energy per hectare) and the threshold of the density of production per hectare that would be required to be self-sufficient according to the *demographic pressure*;

(ii) the actual *labor productivity* (intensity of the internal supply of food energy per hour of labor) and the threshold of the density of production per hour of labor that would be required to be self-sufficient according to the *Bio-Economic Pressure*.

The pattern of correlation of the two values of: (i) actual density of food energy supply per hectare of arable land in

TABLE 2
A comparison between levels of productivity per ha and per hour: (i) actually achieved, and (ii) needed for self-sufficiency

	Land Productivity (actual Supply) (GJ/Ha)		Demographic Pressure (needed for self-sufficiency) (GJ/Ha)		Labor Poductivity (actual Supply) (MJ/hr)		Bio-Economic Pressure (needed for self-sufficiency) (MJ/hr)	
Country	1991	2003	1991	2003	1991	2003	1991	2003
Argentina	14,8	22,8	6,4	7,3	137,3	226,3	59,1	72,5
Australia	6,9	12,8	2,7	4,4	344,2	700,1	135,3	238,8
Bangladesh	35,6	54,0	41,1	62,1	4,6	5,8	5,3	6,6
Burundi	15,1	14,1	15,4	14,8	3,5	2,9	3,5	3,1
Canada	13,3	13,1	6,7	9,4	712,8	943,2	359,4	679,3
China	42,5	40,2	44,5	41,9	5,6	6,1	5,9	6,3
Costa Rica	31,9	41,6	30,5	44,7	26,6	33,5	25,4	36,0
Egypt	84,8	93,3	136,1	146,3	14,6	18,7	23,5	29,4
France	46,3	42,7	25,3	27,7	341,4	535,3	186,7	346,9
Germany	54,1	57,1	49,2	58,6	209,9	390,5	190,9	400,6
Ghana	16,0	17,6	17,3	19,2	8,0	9,6	8,6	10,4
India	18,3	22,3	18,6	23,6	6,6	6,9	6,8	7,3
Italy	14,4	28,3	15,3	39,8	42,5	130,6	45,1	183,7
Japan	50,5	50,4	141,4	147,1	29,6	51,7	82,9	150,9
Mexico	16,6	20,6	20,7	29,2	25,3	33,2	31,5	47,0
Netherlands	112,5	121,9	166,5	210,3	166,4	253,4	246,2	437,2
Spain	16,8	21,9	17,2	27,4	92,4	175,7	94,6	220,0
Uganda	11,8	15,7	12,0	16,7	5,3	5,9	5,4	6,3
UK	53,6	61,3	55,7	75,0	296,1	349,3	307,8	427,4
US	20,1	27,1	16,8	21,9	526,7	836,4	439,6	673,8
Zimbabwe	11,2	8,7	10,6	11,5	5,2	4,1	4,9	5,4

production; and (ii) needed density of food energy supply per hectare of arable land to be self-sufficient is illustrated in Figure 1. The graph shows that the original correlation found in 1991, remained throughout the time window—the movement of the values over time has been on a diagonal to arrive to the points recorded in 2003. This confirms the findings of previous studies (Giampietro, 1997b; Conforti and Giampietro, 1997). That is, the countries that have high demographic pressure (DP) tend to have a high production of food energy per hectare. The group of countries that have the highest demographic and land productivity are the Netherlands, Egypt and Japan. Another cluster includes the United Kingdom, Germany and Bangladesh. For a cluster analysis over this type of comparison see Conforti and Giampietro (1997).

In other words, current technological performance in agriculture in terms of yield per hectare is affected by existing demographic pressure.

The same analysis, referred to the intensity of food production (actual versus needed) per hour of labor is illustrated in Figure 2. The two values of: (i) actual intensity of food energy supply per hour of work in agriculture in production; and (ii) needed intensity of food energy supply per hour of work in agriculture to be self-sufficient, originally correlated over the sample in 1991, keep the same pattern in 2003. Also in this case the

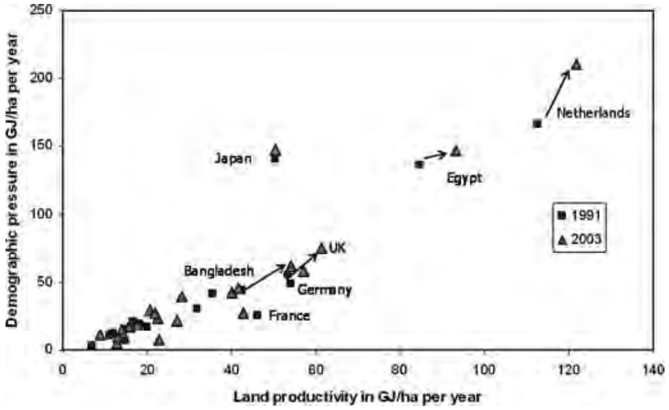

FIG. 1. Land productivity versus demographic pressure.

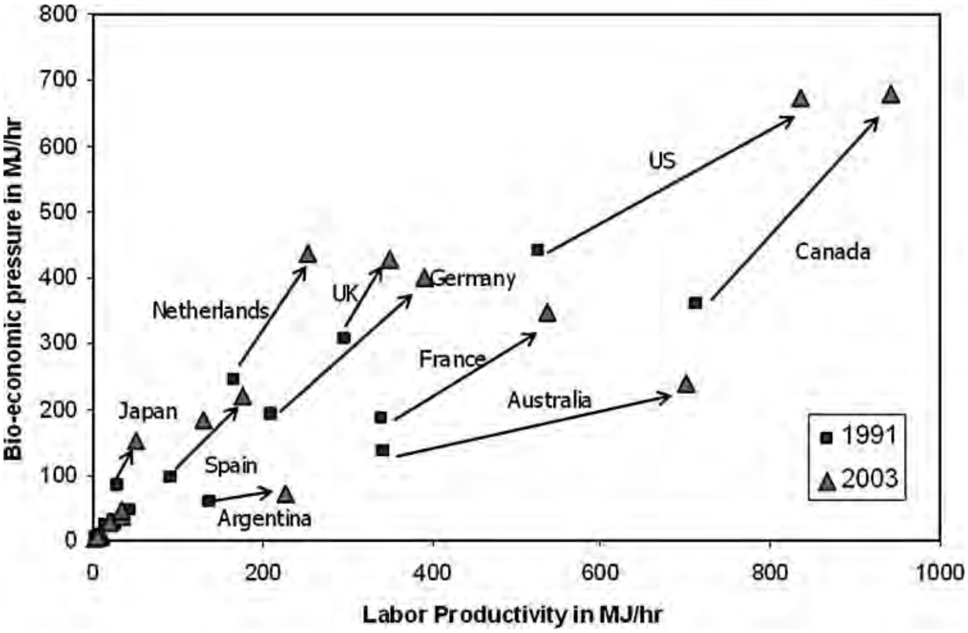

FIG. 2. Labor productivity versus bio-economic pressure.

movement of the values has been on a diagonal. That is, the countries that have a high Bio-Economic Pressure tend to have also a high production of food energy per hour of labor in their agricultural sector.

In this analysis we can observe three groups for developed countries, which all have increased their intensity of the flow of energy per hour over the given time window: (a) those that had the BEP already very high: USA by 53%, and Canada by 89%; (b) those that had medium high: Australia by 76%, France by 85%, Germany by 109%, UK by 53% and Netherlands by 77%; (c) those that had a BEP low in relation to the standard of developed countries: Spain, Japan, and Italy. All the other developing countries remained more or less stable in relation to the intensity of production per hour (as will be discussed later). Argentina is a special case, being a country which is an important food exporter with abundant land per capita. Hence, this analysis confirms that technological performance in agriculture in terms of actual labor productivity is definitely affected by changes in Bio-Economic Pressure (which reflects increasing levels of consumption), but this effect is more evident in developed countries.

What are the implications of this fact? The idea that the various countries included in the sample strive for self-sufficiency in food production is, of course, a simplification of reality. We all know that in a globalized world international trade plays a significant role in stabilizing equilibrium between the requirement and supply of food (Giampietro, 1997b). As a matter of fact, the majority of the countries included in this sample are net food importers (see Table 1). Still, it is important to observe that even those countries that heavily rely on food imports, e.g., Japan, because of their high demographic pressure tend to use in a more intensive way their land in order to produce as much as possible food on their own land.

In general terms we can say that the effect of demographic growth has implied that the arable land per capita has been decreasing over all the 21 countries, when considering the difference between 1991 and 2003. However, as illustrated in Figure 3, the overall decrease in arable land per capita does not coincide with an analogous reduction in arable land per farmer. In fact, a dramatic reduction of the number of farmers in the economy of modern societies, can offset the reduction of arable land per capita due to an increase in DP and imply an increase in arable land per farmers due to an increase in BEP.

For instance, looking at our data set the arable land per capita in 1991, this value is about the same for the United States (0.72 ha) and Argentina (0.83 ha) whereas the arable land and permanent crops per agricultural worker is much larger in the United States (52 ha) than in Argentina (18 ha). The same type of difference, determined by the difference in the fraction of farmers in the work force of the two countries, remained in 2003. The arable land per capita was still similar in the U.S. (0.59 ha) and for Argentina (0.75 ha) in 2003. Still, again, the amount of arable per farmer was much large in the U.S. (61 ha) than in Argentina (19 ha) due to the much smaller percentage of farmers in the labor force in the United States.

Similarly, densely populated European countries, such as Germany France, Italy and the UK, have limited amount of arable land per capita—in the range of 0.12–0.20 ha per capita. These values are comparable with the values of arable land

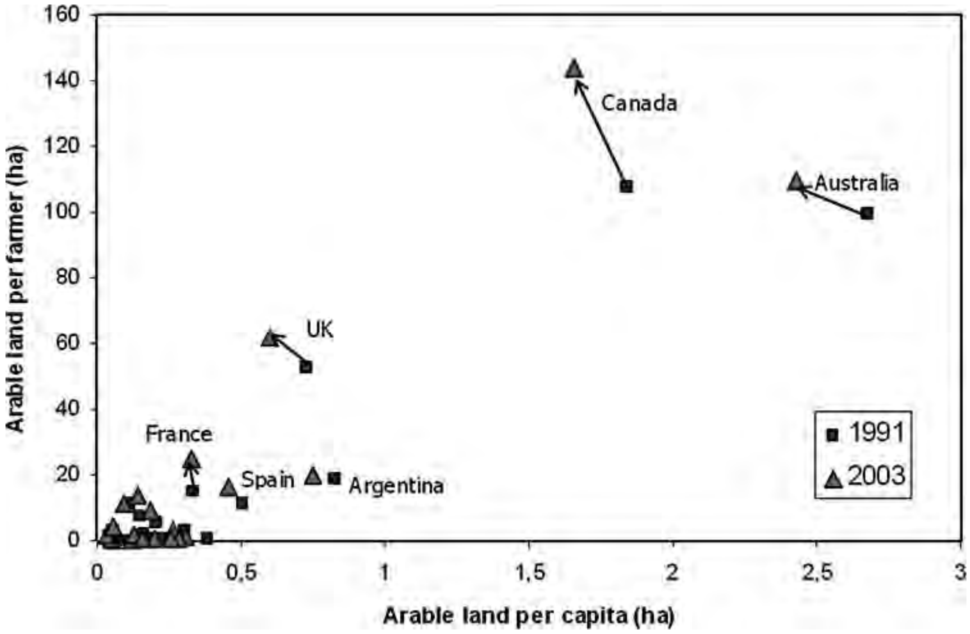

FIG. 3. Arable land per capita versus arable land per farmer.

available per capita in India or Burundi. However, the percentage of farmers in the work force of European countries (around 2% in 1991 and around 1.5% in 2003) is much smaller than the values found in developing countries (e.g., 49% in 1991 and 47% in 2003 for Burundi or 42% in 1991 and 38% in 2003 for China). This implies that, at the same level of DP, the amount of arable land per farmer is larger in countries having a higher level of BEP.

This last observation requires looking at another relation implied by the theoretical framework adopted in this study. The increase in Bio-Economic Pressure (the reduction of the fraction of farmers in the work force) is directly associated with the level of economic growth—the level of GDP—of a society. As illustrated in Figure 4 both the fraction of the work force in agriculture and the fraction of GDP from agriculture decrease dramatically for countries with high levels of GDP. No developed country has a percentage of work force in agriculture larger than 5%. The pattern is pretty robust over the considered time window.

B. Technological Inputs Dealing with Increase in Demographic Pressure (How to Boost Land Productivity with Irrigation and Fertilizers)

1. *Irrigation*

Irrigation is a costly way to augment the yield per hectare. Apart from scarcity of water (Postel, 1997), irrigation requires expensive fixed investments and large energy inputs for operation. For example, a corn crop producing 9,000 kg/ha requires about 7 million liters of water (Pimentel *et al*., 2004). Irrigated corn in Nebraska requires three times more fossil energy than a rainfed corn crop in eastern Nebraska producing the same yield (Pimentel *et al*., 2004). The relationship between land availability and the use of irrigation for the sample of selected countries is shown in Figure 5. It shows that the more a country is faced with land constraints, the more its agriculture relies on irrigation. Exceptions are Burundi, Ghana, Uganda, and Zimbabwe, which are located in the humid tropics or subtropical areas of Africa and have sufficient rainfall (we are referring to national averages).

When checking the relationship between changes in GDP per capita and changes in the use of irrigation over the period 1991 and 2003 we find (as illustrated in Figure 6) that increases in Bio-Economic Pressure associated with increases in GDP p.c. do not necessarily translate in an increase of irrigation (Giampietro, 1997b; Giampietro *et al*. 1999). This analysis confirms the point that the input of irrigation is applied to augment the yields per hectare, and that therefore it is not directly related to the need of increasing the productivity of farm labor.

2. *Nitrogen fertilizer*

The rise of N in fertilizer has increased worldwide of about 150% in many crops (Frink *et al*., 1999). In addition to its growing use, the N fertilizer is the most ‘expensive’ technical input in terms of fossil energy. This is the reason why we are focusing on the use of the N fertilizer as the representative of the entire class of fertilizers.

The relationship between land availability and use of nitrogen fertilizer, shown in Figure 7, indicates that agriculture in countries with land shortage tends to use as much fertilizer as possible. Like for the input of irrigation we can say that—when considering the picture obtained at a large scale—the input fertilizer is applied to augment yield per hectare. That is, the use

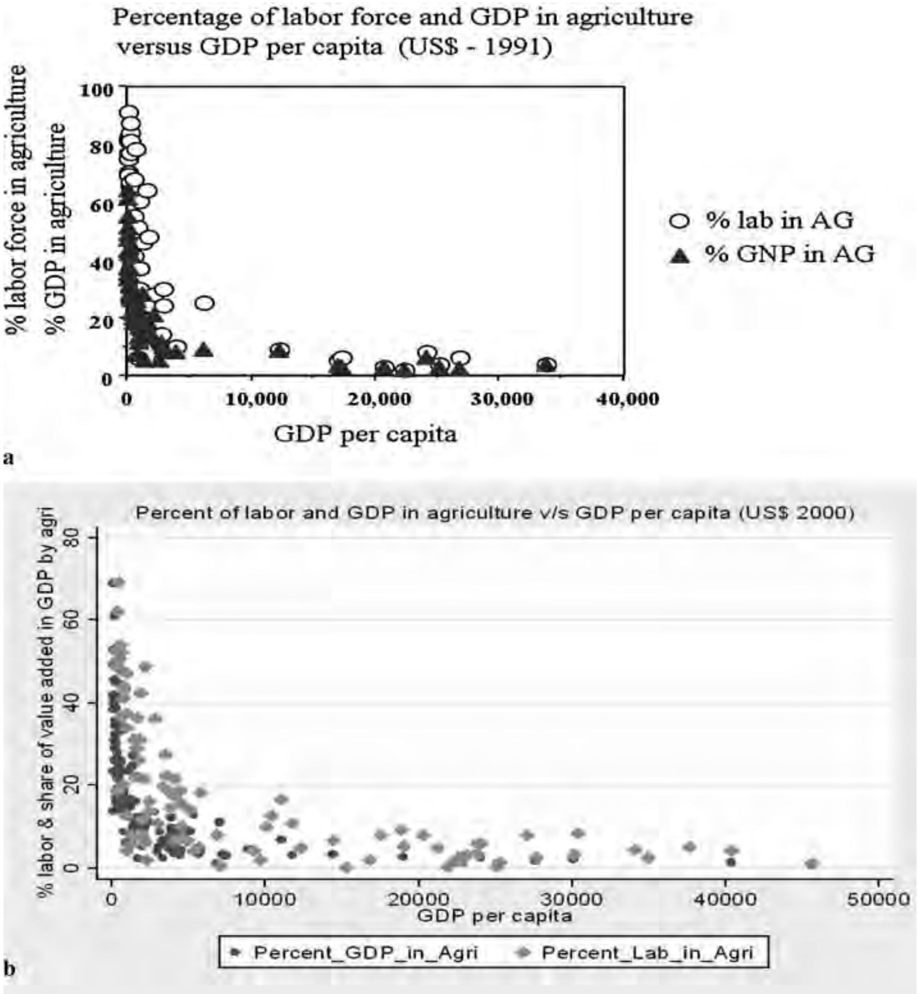

FIG. 4. Economic development and marginalization of the agricultural sector (NOTE Fig. 4a and 4b are provided also as attached files).

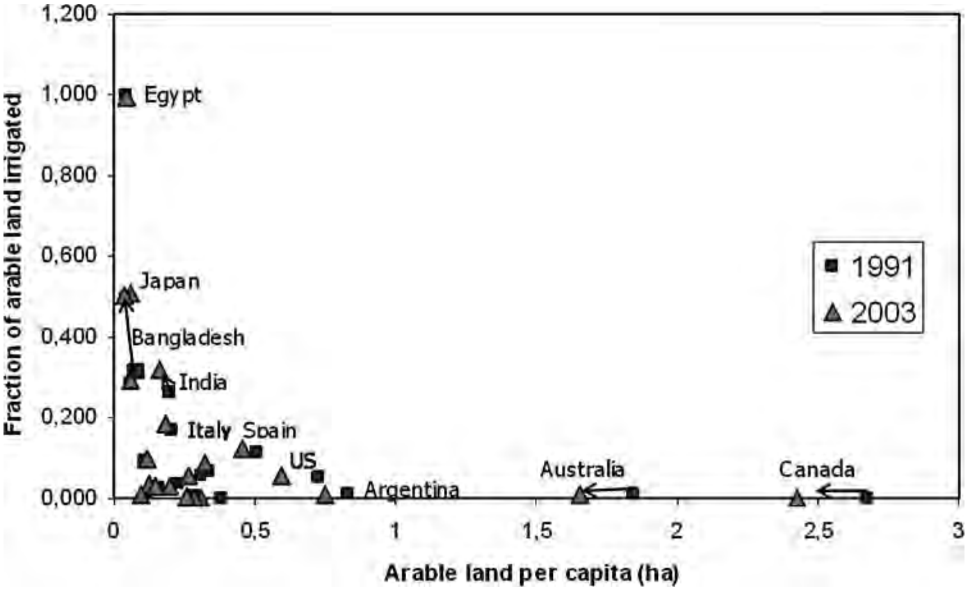

FIG. 5. Land availability versus use of irrigation.

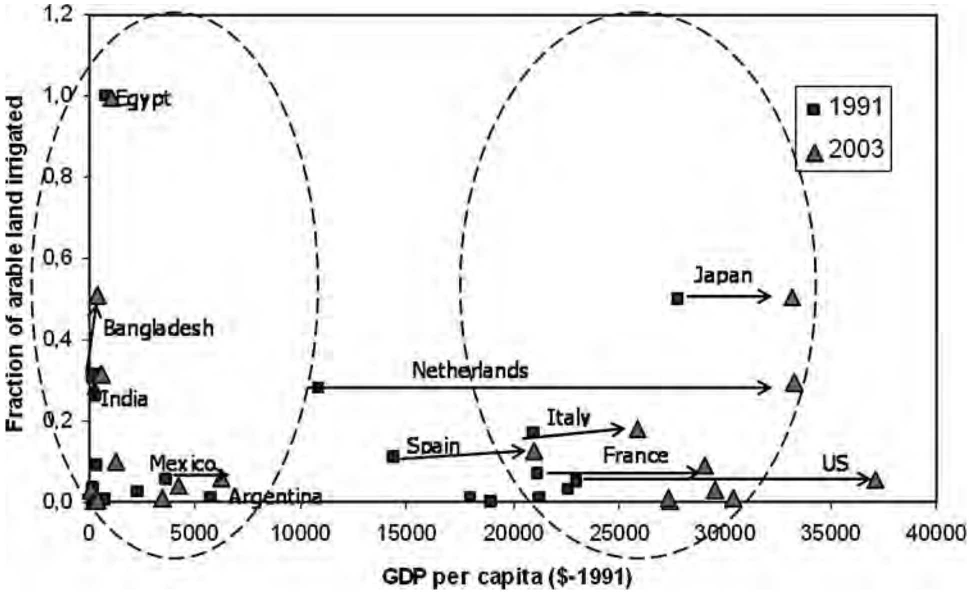

FIG. 6. GDP versus arable land irrigated.

of this input is not directly related to the need of increasing the productivity of farm labor.

When nitrogen use is put in relation with GDP per capita (Figure 8), we can see a clear division between developed and developing countries. Within each of these two groups, nitrogen use appears to be related to scarcity of arable land (according to the pattern observed in Figure 7). Changes related to changes in GDP (the differences between the year 1991 and 2003), shows that in some countries—notably The Netherlands reducing the consumption of 43%—the consumption of fertilizer has been adjusted, optimizing its use in relation to economic performance and environmental impact (reducing the leakage of P and N in the water table).

C. Technological Inputs Dealing with Increase in Bio-economic Pressure (How to Boost Labor Productivity with Machinery)

1. *Machinery*

The relationship between machinery per farmer and GDP per capita for the 21 selected countries is shown in Figure 9. The use of tractors does indeed appear to be related to the level of GDP, which in turn translates into the need to achieve high labor productivity for farmers. Although densely populated countries, such as Japan and some of the European countries with limited amount of arable land, make this relation nonlinear.

In this graph it is clear that tractors are used only by developed countries with the exception of special countries having the option of becoming grain exporters (Argentina in our sample).

A crucial factor determining the use of tractors is land availability, which depends on the available land per farmer—this is to say on demographic pressure, economic development and land tenure. This relation is illustrated in Figure 10, which puts tractor use per farmer in relation to land availability per farmer.

From this graph one can see that agricultural sectors facing shortage of arable land are less likely to increase their use of machinery per farmer, especially in developing countries. By looking at the changes taking place in developed countries we can notice that the use of Tractors and Harvesters reflects the effects of high levels of Bio-Economic Pressure determining a tiny working force in agriculture.

D. Limited Substitutability of Natural Capital with Technological Inputs

Most of the countries of the world are now to some degree dependent on food imports. These imports come from cereal surpluses produced in only a few countries that have a relatively low population density and intensive agriculture. For instance, in the year 2003, the United States, Canada, Australia, and Argentina provided about 45% of net cereal export on the world market (FAO, 2005).

It is easy to guess that if the Demographic Pressure (DP) increases also in exporting countries, they will see their internal grain demand increase and their available arable land per capita decrease. Let us remind here that the value of DP is not only affected by population growth, but also by changes in the diet towards more meat consumption, as the ones reported by Pingali (2006) for Asia. This is so because in the calculation we also include feedstuffs for animals. Under these conditions the cereal grain surplus now exported on the international market may be seriously eroded. This will make even more important the challenge determined by the continuous increase in demographic pressure in those countries which are already importing food.

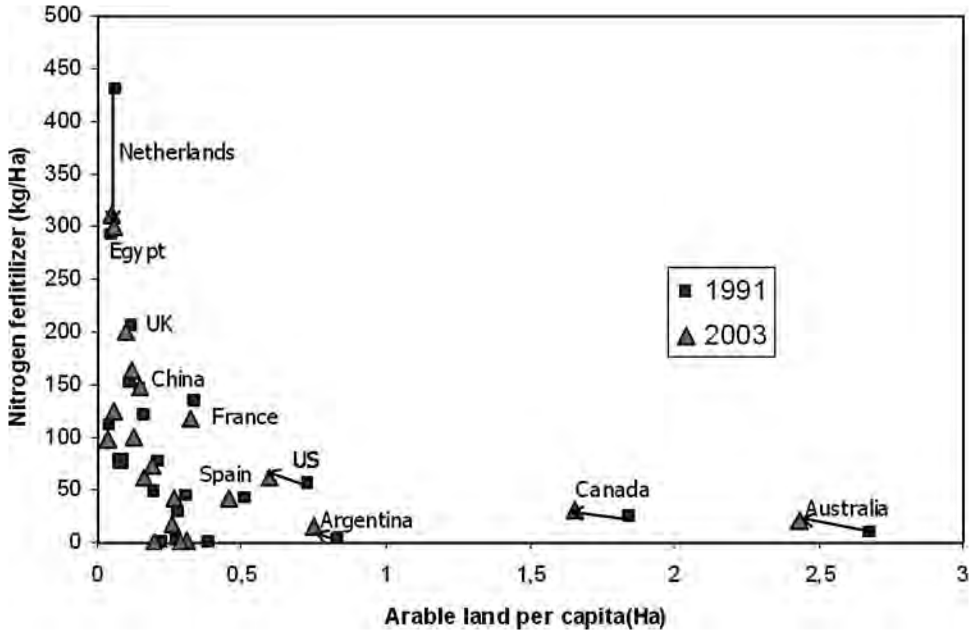

FIG. 7. Arable land versus nitrogen fertilize.

As discussed in the introduction many developing countries rely heavily on fossil energy, especially in form of fertilizers, to sustain their internal food supply. A future slow down of fossil energy consumption because of either a decline of oil supplies, increase in oil prices, or growing restrictions on fossil fuel use to limit its environmental impacts may very well generate a direct competition between fossil energy use in developed countries, to sustain a high standard of living, and that in developing countries, to provide an adequate food supply for survival (Pimentel and Giampietro, 1994b). The recent food crisis generated by large scale agro-biofuel production can be interpreted as a first example of this problem (Giampietro and Mayumi, 2009).

On the other hand, it is obvious that the ability of boosting labor productivity of farmers by using more machinery makes only sense in presence of the availability of a large amount of arable land per farmer. The relation between arable land per farmer and labor productivity is shown in Figure 11. This figure shows that at a given point in time, there is a clear relation between

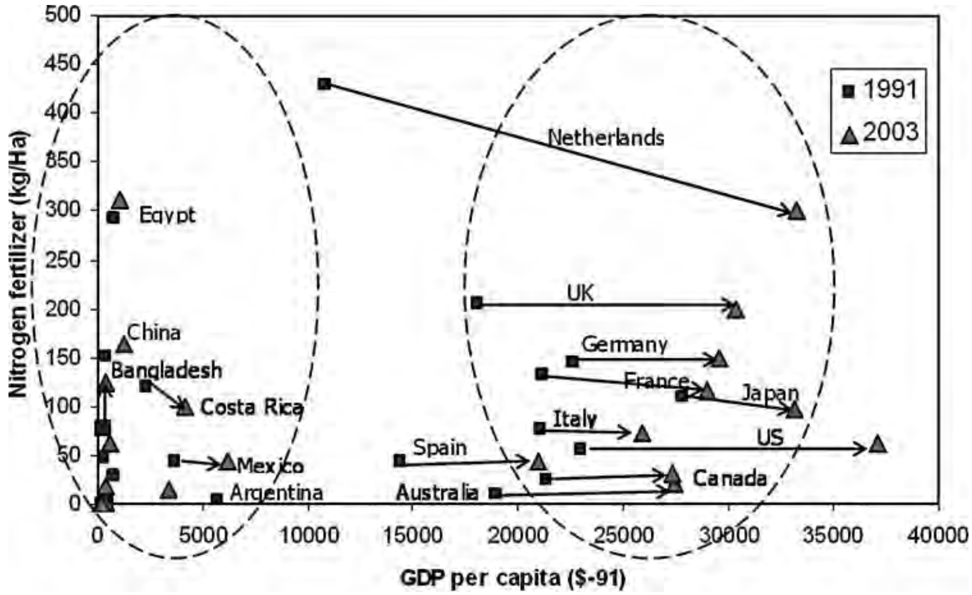

FIG. 8. GDP versus Nitrogen fertilizer.

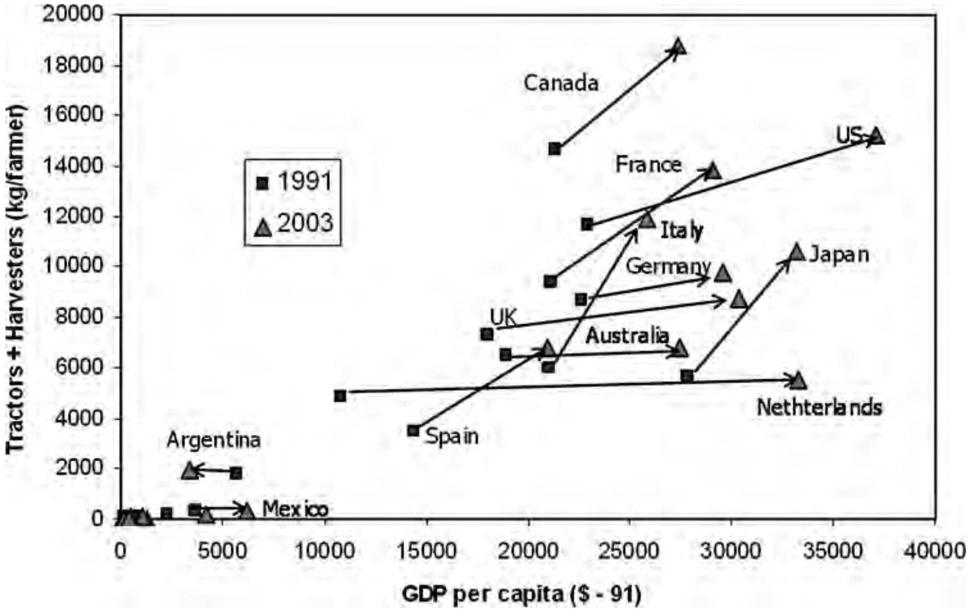

FIG. 9. GDP versus tractors-harvesters.

availability of arable land and labor productivity. This relation, however, can be established only by the use of an increasing amount of tractors. This is to say that countries like Australia, Canada, and the United States have the highest labor productivity but also the largest use of machinery and the largest use of arable land per farmers—the three things go together. Actually, the major increase in productivity of labor in these countries can be associated to a major increase in the use of machinery, e.g., Australia had an increase of 100% in the crop output: from 700 MJ/worker/year in 1991 to 1400 MJ/worker/year in 2003. The possibility of intensifying the use of tractor per farmers, however, depends on the availability of a huge amount of arable land (e.g., more than 100 ha) per agricultural worker.

Different is the situation of the other European countries where agriculture is evidently subject to severe biophysical constraints in terms of shortage of arable land per farmer (when compared with Australia or the United States), a consequence of demographic pressure.

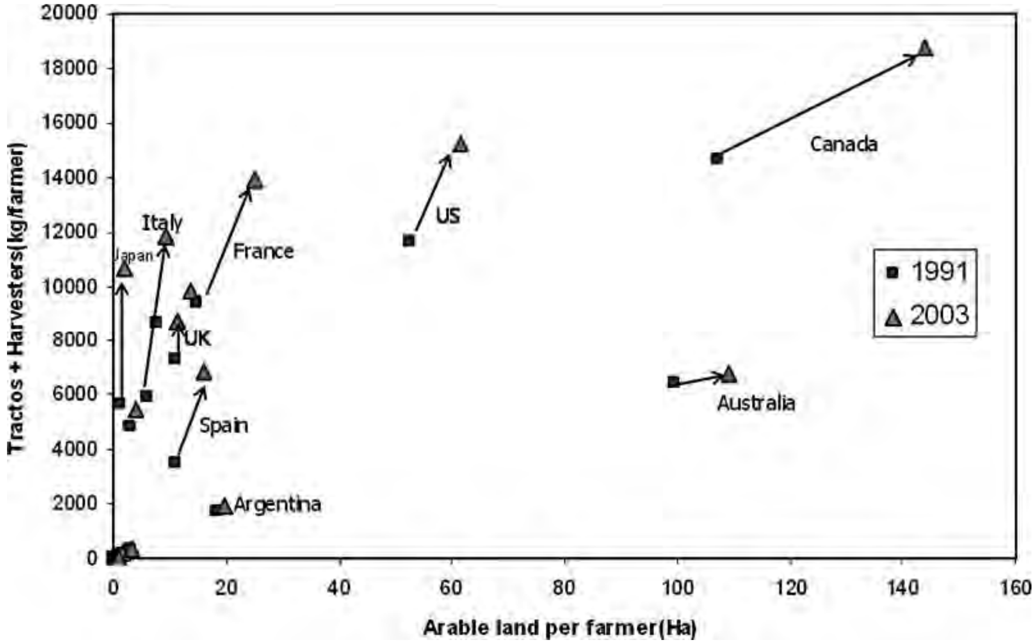

FIG. 10. Arable land versus tractors-harvesters.

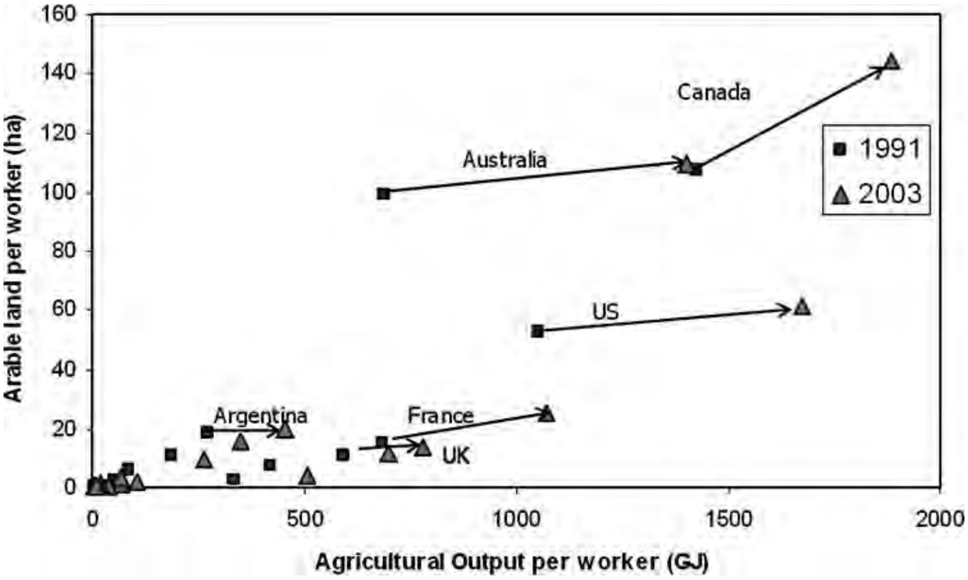

FIG. 11. Agricultural output versus arable land.

E. Technological Inputs and Demographic and Bio-Economic Pressure

The relationship between productivity of land and productivity of labor in agriculture is depicted in Figure 12 and reveals some interesting trends. For instance, the United States and Canada agriculture have a lower performance in terms of yield per hectare than agriculture in Bangladesh, China, Costa Rica, Ghana, Egypt, and the European Union.

On the other hand, U.S. agriculture has the best performance in terms of labor productivity. China, with its huge population, suffers such a severe shortage of arable land that all technological and fossil energy inputs appear to go into raising land productivity with little regard for farm labor productivity.

The Netherlands and Egypt have a high land productivity increasing from 1991 to 2003 as well as the labor productivity. This pattern, however, is not present in other countries. These data indicate that for the 21 agricultural systems studied, the purpose of energy and technological inputs used in agriculture is not necessarily the same. Differences are related to different definitions of 'efficiency' for agriculture depending on the different levels of bio-economic and demographic pressure affecting societal choices.

F. The Overall Pattern of Energy Consumption in Agriculture

The consumption of fossil energy in agriculture can be divided in two categories: direct and indirect. Direct consumption of energy refers to the consumption of fuels for operating machineries, irrigation pumps, heating greenhouses and the moving loads, the consumption of electricity for drying crops, heating and illumination—that is energy spent in the agricultural sector. Indirect consumption of fossil energy refers to the energy spent in the industrial sector for the production of the technological inputs used in agriculture. This indirect consumption includes the production of fertilizers and pesticides (in the chemical sector), the fabrication of machinery (in the mechanical sector) and the fabrication of other infrastructures. For this reason, it is normal to find a discrepancy between the estimates of energy consumption of the agricultural sector found in national statistics and the estimates based on the accounting of direct and indirect fossil energy consumption, which include also the embodied energy in the technical inputs.

To clarify this issue, an overview of the contribution of the different forms of energy is provided in Table 3. In relation to the calculation of this table, we assumed in other inputs a flat rate of 5% of the sum of other technical inputs required for primary production; for example, infrastructure (commercial buildings, fences), electricity for on-farm operations (e.g., drying of crops), energy for heating and energy inherent in use of vehicles and fuels for transportation (Giampietro, 2002).

When interpreting this data set against the rationale adopted in this study, we can observe that countries with high GDP per capita and high demographic pressure, such as Japan and the Netherlands, have a high consumption of fossil energy both per hectare and per worker. Countries with high GDP per capita but relatively low demographic pressure, such as the United States, Canada, and Australia, have high consumption of fossil energy per farmer (to achieve high labor productivity) but relatively low energy consumption per hectare of arable land. Between these countries we can observe in European countries like France, UK, Germany, Italy and Spain. The opposite is true for countries with high population density and low per capita income, such as China and Egypt, which basically invest important amount of fossil energy, but only to boost the productivity of food per hectare.

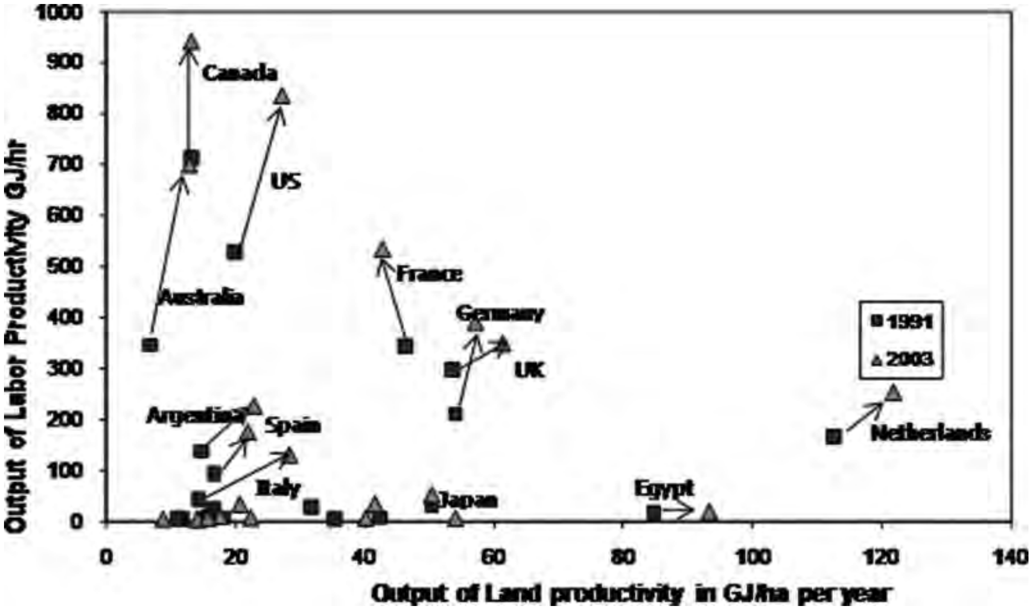

FIG. 12. Output of land productivity versus output of labor productivity.

This observation suggests that we should expect a mosaic of different solutions to the challenge of a sustainable food production, especially when considering that other biophysical constraints, e.g., availability of water, soil, climatic conditions, and ecological constraints, e.g., the level of destruction of natural habitats, which are needed for biodiversity preservation, are different in different areas of the world. This is to say, that it is not reasonable to expect that the future technical progress of agriculture, even when discussing of agro-ecological solutions should be obtained by implementing a common pattern all over the world. Rather than looking for technological packages to be applied all over the planet (extensive adaptation), without regards for the local specificity, we should be looking for specific solutions tailored on the specificity of different situations. When dealing with the sustainability of agriculture “one size does not fit all.”

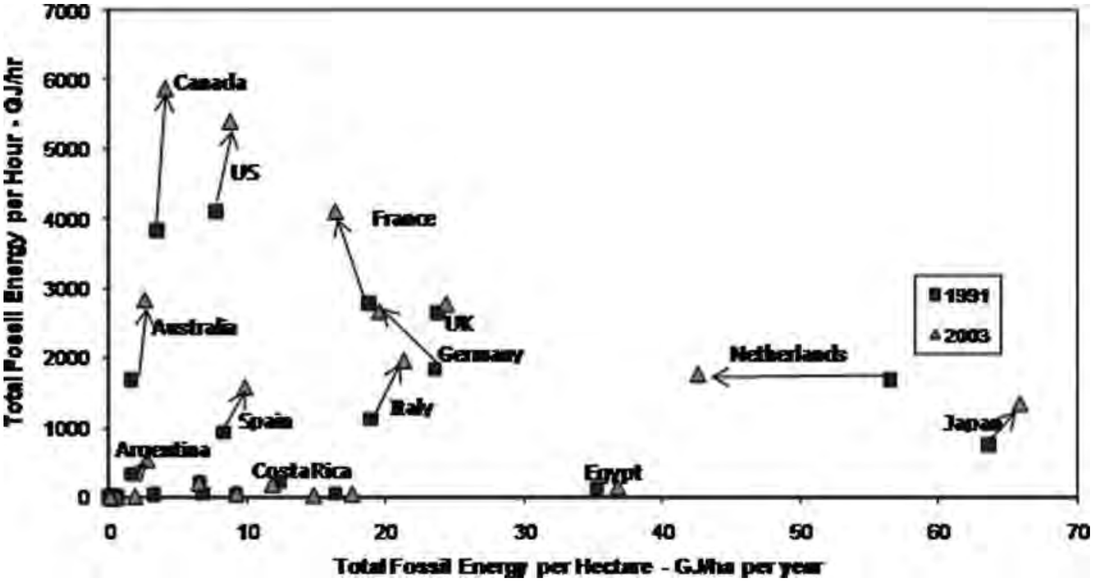

FIG. 13. Total fossil energy per hectare versus per hour.

TABLE 3

Fossil energy input in agricultural production for selected countries

	Indirect Energy Inputs										Direct Energy Inputs															
	Nitrogenous (PJ)		Phosphate (PJ)		Potash (PJ)		Machinery (PJ)		Pesticides (PJ)		Total Indirect Indirect (PJ)		Irrigation (PJ)		Fuel (PJ)		Other inputs (PJ)		Total Direct (PJ)		Estimated Grand Total (PJ)		Reported in Statistics (PJ)	
	1991	2002	1991	2002	1991	2002	1991	2002	1991	2000	1991	2002	1991	2002	1991	2003	1991	2003	1991	2003	1991	2003	1991	2003
Argentina	13,1	13,1	0,9	4,9	0,2	0,3	25,8	28,0	0	0	40,1	46,3	13,1	13,1	50,8	55,1	5,2	5,7	69,1	73,9	109,2	120,1	69,0	113,4
Australia	0,4	0,4	11,8	18,7	1,9	3,1	29,8	29,7	50,3	0,0	94,2	51,9	0,4	0,4	58,7	58,5	7,7	5,5	66,7	64,4	160,9	116,3	46,2	77,7
Bangladesh	25,3	38,5	3,8	3,9	1,1	2,0	0,4	0,4	1,2	2,7	31,9	47,5	25,3	38,5	0,7	0,7	2,9	4,3	28,9	43,6	60,8	91,0	11,2	24,9
Burundi	0,7	0,7	0,02	0,01	0,01	0,01	0,01	0,01	0,1	0,1	0,8	0,8	0,7	0,7	0,02	0,02	0,1	0,1	0,8	0,8	1,6	1,7	—	
Canada	6,0	6,6	10,3	11,1	4,5	4,7	70,9	67,9	0	0	91,7	90,2	6,0	6,6	199,4	190,9	14,9	14,4	220,3	211,8	312,0	302,0	84,6	94,2
China	405,0	459,8	126,5	172,3	32,9	57,3	67,2	108,6	0,1	0,02	631,6	798,1	405,0	459,8	113,4	183,3	57,5	72,1	575,8	715,2	1207,4	1513,2	463,4	718,9
Costa Rica	0,7	0,9	0,3	0,6	0,5	0,9	0,6	0,7	0	16,9	2,1	19,9	0,7	0,9	1,2	1,3	0,2	1,1	2,1	3,3	4,1	23,2	1,4	4,8
Egypt	25,4	32,7	2,6	2,5	0,5	0,8	4,9	7,4	4,6	0	38,1	43,3	25,4	32,7	8,3	12,4	3,6	4,4	37,3	49,6	75,3	92,9		1,9
France	17,6	21,8	21,8	12,7	23,8	13,0	122,6	108,4	35,8	40,9	221,6	196,7	17,6	21,8	241,3	213,4	24,0	21,6	282,9	256,8	504,5	453,5	118,3	94,7
Germany	4,0	4,1	9,0	5,7	10,0	6,5	131,3	86,3	23,3	24,3	177,6	126,8	4,0	4,1	258,5	169,9	22,0	15,0	284,5	189,0	462,1	315,8	103,5	70,0
Ghana	0,1	0,1	0,0	0,1	0,0	0,1	0,3	0,3	0,0	0,1	0,4	0,7	0,1	0,1	0,6	0,5	0,1	0,1	0,7	0,7	1,1	1,4	1,6	8,2
India	397,0	478,7	57,7	69,5	18,6	22,2	85,3	202,6	59,4	0,0	618,0	773,1	397,0	478,7	143,9	341,9	57,9	79,7	598,8	900,3	1216,8	1673,4	54,6	241,5
Italy	22,7	23,0	11,5	6,5	5,7	3,7	120,3	137,4	71,5	63,2	231,6	233,8	22,7	23,0	236,8	270,5	24,6	26,4	284,0	319,9	515,7	553,7	103,5	117,1
Japan	23,6	21,8	12,1	8,4	6,6	4,6	250,8	245,6	0	0	293,1	280,4	23,6	21,8	423,2	414,5	37,0	35,8	483,9	472,1	777,0	752,5	89,6	117,2
Mexico	48,5	52,9	6,6	6,1	1,2	2,5	26,9	27,8	0	0	83,2	89,3	48,5	52,9	53,0	54,7	9,2	9,8	110,8	117,5	194,0	206,7	73,1	89,8
Netherlands	4,7	4,7	1,3	0,9	1,3	0,9	15,0	12,4	0	0	22,3	18,9	4,7	4,7	29,5	24,4	2,8	2,4	37,0	31,6	59,3	50,5	11,8	20,7
Spain	28,4	31,6	8,7	10,4	5,2	6,6	64,4	79,5	13,4	15,0	120,0	143,2	28,4	31,6	126,7	156,6	13,8	16,6	168,8	204,8	288,9	348,0	62,0	85,8
Uganda	0,1	0,1	0,01	0,05	0,01	0,03	0,4	0,4	0,1	0,0	0,5	0.5	0,1	0,1	0,6	0,6	0,1	0,1	0,8	0,8	1,3	1,3	—	
UK	1,4	1,4	6,3	4,9	6,0	5,1	43,8	43,8	25,0	26,5	82,6	81,7	1,4	1,4	86,3	86,2	8,5	8,5	96,2	96,0	178,8	177,7	33,4	12,8
US	174,9	188,3	66,4	67,3	0,0	0,0	416,4	433,8	171,6	0,0	829,4	689,4	174,9	188,3	1171,1	1220,0	108,8	104,9	1454,8	1513,2	2284,2	2202,5	609,4	641,3
Zimbabwe	1,0	1,1	0,7	0,5	0.4	0,3	1,5	0,1	2,2	0,0	5,8	2,0	1,0	1,1	2,5	0,1	0,5	0,2	4,0	1,4	9,8	3,4	2,9	37,5

Source: Giampietro (2002) and calculations on FAOSTAT.

Reported In Statistics: Data from IEA World Energy Statistics and Balances considering Agriculture/Forestry - Petroleum Products.

IV. CONCLUSION

The analysis presented in this paper clearly shows the existence of huge differences in the situation experienced by farmers operating in different contexts (e.g., developed countries versus developing countries; very populated countries versus sparsely populated countries). These differences may be further boosted, in the future, by existing trends of demographic and economic growth. In fact, there are countries in Africa and in America and Asia where population is still growing faster than GDP and countries where the GDP is growing faster than population.

When considering socioeconomic constraints, due to the required high level of investment per farmer (Giampietro, 2008; Giampietro and Mayumi, 2009), in many developing countries it would be impossible to follow the "Paradigm of Industrial Agriculture" which has been implemented in developed countries. In fact, replacing the work of farmers with expensive pieces of machinery and huge injections of technical inputs requires the availability of a lot of capital, the existence of consumers capable of buying expensive food, and the possibility of absorbing the vast majority of rural population into cities where they can work in the industrial or the service sector with productivity that (in economic terms, not in physical terms) is higher than in the villages they left behind. Many developing countries do not have enough money to invest in a capitalization of their agriculture, nor rich consumers which can buy expensive food, nor an economy which can offer well paid jobs in the cities. This point is in favor of alternative techniques of production based on a low dependence on external inputs. As a matter of fact, when looking at the changes in the use of technological inputs over the time window considered in this study, we can notice that tractors, nitrogen and irrigation have increased at the world level, but at considerable different rates in Africa and Europe.

When considering biophysical constraints, a continuous increase in demographic pressure results in the requirement of a continuous increase in food production. Since the best arable land is already in use, this translates into the need of bringing new land under production, expanding irrigated land area and applying Green Revolution technologies also on marginal land. In many countries in Africa, Asia and some countries in South America this translates into a continuous expansion of agricultural production into fragile and ecologically sensitive regions, where yields are lower than in fertile land. This requires a larger use of technical inputs with lower economic return and a much larger environmental impact in terms of loss of habitat for biodiversity preservation. To make things worse, economic development not only tends to reduce the number of farmers, but also to change the mix of food products in the diet of the growing urban population. As a consequence of this fact, in developing countries more people are eating more animal products (dairy and meat). This translates into an increasing quantity of grains consumed per capita, for the supply of animal products. That is, the combination of population and economic growth translates into a major boost in the requirement of food production, and therefore a major boost to the stress on terrestrial and aquatic ecosystems.

Nobody can predict the future of agriculture in 50 years from now. What we can say is that it is very unlikely that the future technical development of agriculture will continue by doing "more of the same" as done right now. For this reason it is important to study alternative systems of agricultural production capable of generating a diversity of performances, which can be selected in different contexts in relation to different criteria and different typologies of constraints.

ACKNOWLEDGMENTS

The authors would like to acknowledge financial support from the following: (i) the Catalan Government for a FI Scholarship to Nancy Arizpe, the Emergent Research Group on "Integrated Assessment: sociology, technology and the environment" SGR2009 – 042496, and the Consolidated Research Group on "Economic Institutions, Quality of Life and the Environment," SGR2009 – 00962; (ii) the European Comission, EuropeAid Cooperation Office funded Alfa project Sustainable Use of Photosynthesis Products & Optimum Resource Transformation (SUPPORT); (iii) the EU funded project "Synergies in Multi-Scale Interlinkages of Eco-Social Systems" (SMILE, Contract 217213-FP7-2007-SSH-1), (iv) the EU funded project "Development and Comparison of Sustainability Indicators" (DECOIN, Contract 044428-FP6-2005-SSP-5A) and (v) the Spanish Ministry for Science and Innovation Projects SEJ2007–60845 and HAR–2010–20684–C02–01.

REFERENCES

Altieri, M. A., Anderson, M. K., and Merrick, L. C. 1987. Peasant agriculture and the conservation of crop and wild plant resources. *Conservation Biol.* **1**: 49–58.

Boserup, E. 1981. *Population and Technological Change.* The University of Chicago Press, Chicago.

Conforti, P., and Giampietro, M. 1997. Fossil energy use in agriculture: an international comparison. *Agriculture, Ecosystems & Environment* **65:** 231–243.

Cottrell, W. F. 1955. *Energy and Society: The Relation between Energy, Social Change, and Economic Development*. McGraw-Hill, New York.

FAO (Food and Agriculture Organization of the United Nations). 2005. FAOSTAT Online Statistical service, Rome. Available online at: http://faostat.fao.org. Accessed on 23 November 2009.

FAO (Food and Agriculture Organization of the United Nations). 2009. *Food Price Indices. World Food Situation*. Available online at: http://www.fao.org/worldfoodsituation. Accessed on 18 January 2009.

Frink, C., Waggoner, P., and Ausubel. J. 1999. Nitrogen fertilizer: Retrospect and prospect. *PNAS* **96:**1175–1180.

GRAIN. 2008. *The 2008 land grab for food and financial security.* GRAIN Briefing. October 2008. Available online at http://www.grain.org/briefings_files/landgrab-2008-en.pdf. Accessed on December 2008.

Gever, J., Kaufmann, R., Skole, D., and Vörösmarty, C. 1991. *Beyond Oil: The Threat to food and Fuel in the Coming Decades*. University Press of Colorado, Niwot. CO.

Giampietro, M. 1997a. Socioeconomic constraints to farming with biodiversity. *Agriculture, Ecosystems & Environment* **62:**145–167.

Giampietro, M. 1997b. Socioeconomic pressure, demographic pressure, environmental loading and technological changes in agriculture. *Agriculture, Ecosystems & Environment* **65:** 201–229.

Giampietro, M. 2002. Energy use in agriculture. **In:** *Encyclopedia of Life Sciences*. Nature Publishing Group. Accessible at: http://www.els.net/. Accessed on January 2003.

Giampietro, M. 2003. *Multi-Scale Integrated Analysis of Agro-ecosystems.* CRC Press, Boca Raton, FL, 472 pp.

Giampietro, M. 2008. The future of agriculture: GMOs and the agonizing paradigm of industrial agriculture. **In:** *Science for Policy: Challenges and Opportunities* pp 83–104.

Guimaraes Pereira, A. and Funtowicz, S., Eds., Oxford University Press, New Dehli.

Giampietro, M., Bukkens, S. G. F., and Pimentel, D. 1994. Models of energy analysis to assess the performance of food systems. *Agricultural Syst.* **45:** 19–41.

Giampietro, M., Bukkens, S. G. F., and Pimentel, D. 1999. General trends of technological changes in agriculture. *Crit. Rev. Plant Sci.* **18:** 261–282.

Giampietro, M., and Mayumi, K. 2000. Multiple-scale integrated assessment of societal metabolism: Integrating biophysical and economic representations across scales. *Population and Environment* **22:** 155–210.

Giampietro, M., and Mayumi, K. 2009. *The Biofuel Delusion: The Fallacy behind Large-scale Agro-biofuel Production.* Earthscan Research Edition, London.

Giampietro, M., and Pimentel, D. 1994. Energy utilization in agriculture.**In***:* *Encyclopedia of Agricultural Science 2*. pp. 63–76, Arntzen, C. J., and Ritter, E. M., Eds., San Diego (CA), Academic Press, Inc.

Hayami, Y., and Ruttan, V. 1985. *Agricultural Development. An International Perspective.* 2nd ed. The John Hopkins University Press, Baltimore, MD, USA.

Heinberg, R. 2007. The essential re-localisation of food production. **In:** O*ne Planet Agriculture. Preparing for a Post-Peak Oil Food and Farming Future.* pp 13–17, Hopkins R., and Holden P., Eds., Soil Association, Scotland.

Hesel, Z. 1992. Energy and alternatives for fertilisers and pesticide use. **In:** *Energy in Farm Production. Energy in World Agriculture.* **6**, Fluck R.C., and Stout, B. A., Eds., Elsevier, Amsterdam.

IMF (International Monetary Fund). 2007. *World Economic Outlook. Globalization and Inequality*. Whasington, DC. October 2007. http://www.imf.org/external/pubs/ft/weo/2007/02/pdf/text.pdf. Accesed on March 30, 2008.

Krugman, P. 2008. *Grains gone wild*. New York Times, April 7, 2008. http://www.nytimes.com/2008/04/07/opinion/07krugman.html. Accesed on April 7, 2008.

Leach, G. 1976. *Energy and Food Production*. I.P.C. Science and Technology Press limited, Surrey, U.K.

Odum, H. T. 1971. *Environment, Power, and Society*. Wiley-Interscience, New York.

Paoletti, M. G., Giampietro, M., Chunru, H., Pastore, G., and Bukkens, S. G. F., Eds. 1999. Agricultural intensification and sustainability in China. Special issue of *Crit. Rev. Plant Sci.***18:** 261–282.

Pastore, G., Giampietro, M., and Mayumi, K. 2000. Societal metabolism and multiple-scales integrated assessment: Empirical validation and examples of application. *Popul. Environ.* **22:** 211–254.

Pimentel, D., Ed. 1997. *Techniques for Reducing Pesticide Use: Environmental and Economic Benefits*. John Wiley & Sons, Chichester, U.K.

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, B., Clark, S., Poon, E., Abbett, E., and Nandagopal, S. 2004. Water resources: Agricultural and environmental issues. *Bioscience* **54:** 909–918.

Pimentel, D., Dazhong, W., and Giampietro, M. 1990. Technological changes in energy use in U.S. agricultural production. **In:** *Agroecology.* pp. 305–321, Gliessman, S. R., Ed., Springer, New York,

Pimentel, D., and Giampietro, M. 1994a. Implications of the limited potential of technology to increase the carrying capacity of our planet. *Human Ecol. Rev.* **1:** 249–252.

Pimentel, D. and Giampietro, M. 1994b. *Food, land, population and the U.S. economy*. Report prepared for Carrying Capacity Network (CCN), Washington, DC. http://www.carryingcapacity.org/pubs.htm. Accessed on March 1994.

Pimentel, D., and Pimentel, M. 1979. *Food, Energy and Society*. Edward Arnold, London.

Pimentel, D., and Pimentel, M. 1996. *Food, Energy and Society.* Rev. ed., University Press of Colorado, Niwot, CO.

Pingali, P. 2006. Westernization of Asian diets and the transformation of food systems: Implications for research and policy. *Food Policy* **32:** 281–298.

Postel, S. 1997. *Last Oasis: Facing Water Scarcity.* Revised edition, W. W. Norton, New York.

Ramonet, I. 2009. *Neocolonialismo Agrario*. Le Monde Diplomatique, February, n° 160: 1.

Smil, V. 1987. *Energy-Food-Environment. Realities-Myths-Options*. Clarendon Press, Oxford.

Smil, V. 1988. *Energy in China's Modernization*. M. E. Sharpe, Armonk, NY.

Smil, V. 1991. *General Energetics.* New York, Wiley.

Smil, V. 2001. *Enriching the Earth*. The MIT Press, Cambridge, MA.

Steinhart, J. S., and Steinhart, C. E. 1974. Energy use in U.S. *Food System Sci.* **184:** 307–316.

Stout, B. A. 1991. *Handbook of Energy for World Agriculture.* Elsevier, New York.

Stout, B. A. 1992. Editor in Chief. *Energy in World Agriculture* (6 volumes) Elsevier Amsterdam. The list of volumes includes:

Vol. 1, Singh, R. P., Ed., Energy in Food Processing

Vol. 2, Hesel Z. R., Ed., Energy in Plant Nutrition and Pest Control

Vol. 3, McFate K. L., Ed., Electrical Energy in Agriculture

Vol. 4, Parker B. F., Ed., Solar Energy in Agriculture

Vol. 5, Peart R. M. and Brooks R. C., Eds., Analysis of Agricultural Systems

Vol. 6, Fluck R. C., Ed., Energy in Farm Production

The Guardian, 2008. *Secret report: biofuel caused food crisis - Internal World Bank study delivers blow to plant energy drive*. http://www.guardian.co.uk/environment/2008/jul/03/biofuels.renewableenergy. Accessed on July 3, 2008.

UNFPA (United Nations Population Fund). 2008 *Annual Report,* United Nations Population Fund, New York, NY, www.unfpa.org/upload/lib_pub_file/777_filename_unfpa_ar_2007_web.pdf Accessed on February 2008.

Williams, N. 2009. Alarm bells over Africa land deals. *Curr. Biol.* **19:** 1053–R1054.

Wilson E. O. (Ed.). 1988. *Biodiversity*. National Academy Press, Washington, D.C.

World Bank. 2005. *World Development Indicators.* Washington, D.C. http://devdata.worldbank.org/wdi2005/home.htm. Accesed on March 30, 2010

World Bank. 2008. *Biofuels: The promise and the risks*. World Development Report: http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/EXTWDRS/EXTWDR2008/0,,contentMDK:21501336∼pagePK:64167689∼piPK:64167673∼theSitePK:2795143,00.html Accessed on January 2008.

Critical Reviews in Plant Sciences, 30:64–73, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554353

Ecology in Sustainable Agriculture Practices and Systems

C. A. Francis[1] **and P. Porter**[2]
[1]*Department of Agronomy & Horticulture, University of Nebraska, Lincoln, Nebraska, USA*
[2]*Department of Agronomy & Plant Genetics, University of Minnesota, St. Paul, Minnesota, USA*

Table of Contents

Sustainable and productive agroecosystems must be developed that will meet today's needs for food and other products, as well as preserving the vital natural resource base that will allow future generations to meet their needs. To increase production efficiency, to improve farming strategies based on local resources, and to design systems that are resilient in the face of changing climate require thorough understanding of the ecology of agricultural systems. Organic and sustainable farmers have developed many production practices and integrated crop/animal systems that are finding application in more conventional farming enterprises. While they do seek greater resource use efficiency and substitution of more environmentally benign inputs to replace chemicals used in conventional farming, sustainable farmers increasingly depend on thoughtful redesign of production systems to provide internal management of soil fertility and pests, careful use of contemporary energy and rainfall, and reliance on internal resources rather than imported inputs. Evaluation of systems based on productivity, sustained economic return, viable environmental indicators, and equitable social consequences of agricultural production are central to future sustainable farming and food systems.

Keywords ecological practices, soil fertility, pest management, crop rotations, crop/animal systems, agroecosystems management, conventional agriculture

I. INTRODUCTION: ECOLOGICAL PRINCIPLES IN AGROECOSYSTEMS

An important perspective that has shaped our current thinking about sustainability was suggested by the definition in the report of the World Commission on Environment and Development. In the report *Our Common Future* (WCED, 1987), a logical and functional definition of sustainability emerged: "Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (p. 8). Similar planning was common to Native American groups who made important decisions based on projecting the impacts for seven generations into the future: "In every deliberation we must consider the impact on the seventh generation . . . even if it requires having skin as thick as the bark of a pine," from Great Law of the Iroquois (Murphy, 2001). Henry Wallace, former Secretary of Agriculture and Vice President, called for the durability of agriculture (White and Maze, 1995). More recently these concepts have been incorporated into research and education programs that focus on structure and function of

---

Address correspondence to C. A. Francis, Department of Agronomy & Horticulture, University of Nebraska, Lincoln, Nebraska, USA. E-mail: cfrancis2@unl.edu

Referee: Prof. Gary E. Varvel, Agroecosystem Management Research Unit, University of Nebraska Lincoln, NE 68583.

whole systems, and often conducted under the term *Agroecology* as the ecology of food systems (Francis *et al*., 2003; Gliessman, 2007). In simple terms, thoughtful people across the ages have concluded that we should leave the world to our children in a better condition than the way we found it.

This paper describes the vital role of ecology in shaping the design of sustainable food production systems. Principles of biodiversity, systems resilience, and interconnectedness of components are now being applied in planning research and designing education (see Francis *et al*., 2011, this issue). Most important to systems success are managing soil fertility, crop and animal pests, and integrated farming strategies with diverse crop and animal species dispersed across the farm and rural landscape, and taking into account their impacts on the environment, families, and communities. A useful framework for discussion was provided by MacRae *et al*. (1990), who described improving system performance by increasing efficiency, substituting less costly or more environmentally sound inputs, and ultimately redesigning farming systems to better meet farm family's and society's needs. We conclude with visions of future farming systems, where ecological principles and lessons from organic farming increasingly impact the entire food production and consumption network.

As described in several articles in this issue, it is valuable to examine the sustainability of current conventional agricultural systems and practices and compare this to potential sustainability of alternative practices and systems. Because of the growing research base and increasing understanding of certified organic production systems, these non-synthetic chemical methods of farming provide one convenient option against which to compare conventional systems. Yet this is not the only way to achieve greater sustainability, and in fact every farmer would likely list long-term sustainability of production and profit as essential goals for improved farming systems. In a recent book *Developing and Extending Sustainable Agriculture: a New Social Contract* (Francis *et al*., 2006), a wide range of practices and system changes has been summarized, including the essential environmental and social outcomes of alternative systems. An important focus of this article is on impacts of farming beyond production stability and profits, in keeping with the results of the National Academy of Science report that calls for a greater attention to the multiple outcomes of agricultural research and especially its influence on rural communities (National Research Council, 2003).

Attention to these multiple dimensions of the farming system and the many and complex interactions among farming practices is typical of farmers seeking to develop a sustainable agriculture, and particularly those farmers who are certified for organic production (Drinkwater, 2009). Increases in farm size and need for efficiency of labor use have led to specialization and monoculture in most conventional farming operations, and a common strategy has been to simplify and homogenize the production environment and control as many factors as possible (Meffe *et al*., 2002). Rapid adoption of transgenic technologies such as Roundup© resistant maize and soybeans and several crop species with incorporated Bt have further simplified management of weeds and insects. Yet exclusive use of this technology has accelerated the selection of resistant weeds (330 biotypes, Weed Science Society of America, 2008) and resistant insects (over 500 biotypes, Aldridge, 2008). We are learning from this rapid emergence of genetic resistance to pests that diversity in pesticide use is important to slow the process. In contrast, the introduction of biodiverse crop rotations and in-field spatial diversity includes options for smaller scale organic systems that can help manage pest problems without synthetic chemicals (Liebman and Davis, 2009; Bird *et al*., 2009). This is one example of the importance of ecological principles that are needed in design of farming systems, a topic expanded in later sections.

Before moving to specific examples of sustainable practices in conventional and sustainable systems, it is useful to summarize the major differences or characteristics of systems that are generally categorized in these two groups. Table 1 lists a number of key characteristics that help identify and contrast the resource use and types of practices that result from two different philosophies in farming.

The contrasts are obviously not absolute, for example, as all farming systems in the field depend on incident solar radiation and rainfall plus moisture stored from winter snows. There is fossil fuel used for land preparation, tillage, and harvest in both types of systems. But the use of synthetic chemical fertilizers and pesticides that are essential in conventional systems represents a suite of practices that are not used in many organic and sustainable systems. In such alternative systems, there is often greater efficiency of input use, substitution of other inputs, and redesign of systems to avoid the need for these chemical inputs.

The methodology used to draw comparisons among farming systems described by MacRae *et al*. (1990) needs further explanation and concise examples. Increasing efficiency of input use and system performance are high on the agenda of all farmers, in order to reduce costs of materials and labor. An example is reducing nitrogen application rates as a result of careful soil sampling, analysis, and interpretation of results. The next step up the ladder is substituting one input or practice for another, for example replacing a maize hybrid with one more tolerant to drought to reduce irrigation needs, or substituting a broad-spectrum herbicide for cultivation in order to manage weeds and keep them below the economic threshold. The most complex step is redesign of systems, for example establishing a long-term rotation that includes legumes and cereals, summer with winter crops, or pastures with annual crops in order to achieve more sustainable systems. These principles – efficiency, substitution, redesign — are used in the following sections to describe how researchers are providing new information to improve productivity and profit, and how farmers are adopting these measures in their whole-farm systems.

An overview of the planning process for rotations is found in Figure 1, a schematic that begins with the philosophy and goals of the farmer and results in a profitable and environmentally sound rotation. The natural resource endowment of each

TABLE 1
Comparison of conventional versus sustainable farming systems.

Characteristic	Conventional System	Sustainable System
Primary energy source	Fossil fuels + sunlight	Contemporary sunlight
Source of nutrients	Chemical fertilizers	Manure, compost, rotations, cover crops
Pest management	Chemical applications	Crop rotations, resistant cultivars, tillage
Crop cultivars	Maximum yield potential, GMOs in many systems	Sustainable yield with moderate inputs, no GMOs
Tillage	Moving toward no-till with chemical herbicides	Tillage for weed management
Crop rotations	Short rotations to maximize profits from two crops	Long rotations to seek pest management and fertility
Farm size	Large, and goal often to expand	Small to moderate, goal is to stabilize operation
Labor source	Family plus hired labor for expanded farm size	Family only (if possible) plus hired for specialty products
Crop/animal integration	Specialized in either crops or livestock	Crops and livestock integrated on farm
Number of crops and other enterprises/farm diversity	Limited to two crops, sale to conventional buyers	Diverse mix of crops/animals and sale of diverse products
System resilience	Low, subject to changes in markets, fuel costs	Moderate, income sources buffered by diversity
Level of biodiversity on farm	Low, with monoculture crops and two-year rotation	Moderate to high, with many crops + livestock

place and knowledge of farming by the manager of the current operation will dictate in large part how much *efficiency* can be achieved by modification of input use. *Substitution* of inputs is possible and desirable if the change is in concert with overall goals and philosophy, and if there is labor, equipment and management skill to implement the change. *Redesign* of a system requires much more information, often new or different equipment, and may or may not need more labor. Implementation that follows the design phase will lead to results that may inform further changes in the system. Thus, an iterative process in management is based on lessons learned, and how any modification of the system makes it more productive, more resilient, and ultimately more profitable over time.

We conclude with an exploration of a future vision for farming systems that is based on ecological principles. This strategy builds on information presented in sections on soil fertility, crop and animal protection, and system design with crop/animal integration. Finally, we discuss ways that organic farming and other alternative methods are influencing mainstream farming. There is growing awareness of the unintended challenges that are emerging from our highly specialized current agricultural systems, and we present alternatives that are ecologically sound and provide promise for more resilient and resource-efficient food production systems for the future. Concepts for this discussion build on recent reviews by Kirschenmann (2009) and Francis and Hodges (2009).

II. MAINTAINING SOIL FERTILITY

Efficiency of fertilizer use is one management goal in conventional agriculture driven by high energy prices and environmental regulation. Even the suggestion of applying more than recommended rates of nitrogen or other nutrients to assure maximum yields is today largely a thing of the past. Economics dictate against such practices, and concern about leaching through the root zone and loss by surface soil erosion further reduces the likelihood of overapplication of chemical fertilizers. *Substitution* of green manures as cover crops, animal manure and compost, and grain legumes in the system provide valuable alternatives in organic systems that differentiate them from large-scale, conventional operations (Magdoff and van Es, 2009). *System redesign* to enhance or maintain soil fertility is closely tied to rotations, crop choice, and crop/animal systems, all discussed in later sections.

One of the most important research studies on fertilizer application rates, as based on soil test laboratory recommendations, was conducted by Prof. Robert Olson and colleagues at University of Nebraska. They sent soil samples from the same field and plots to five laboratories, and applied the recommended fertilizer package to maize each year for ten years. At the end of this period, costs of the recommended package from four commercial laboratories were twice those of the recommendation from the university soil test laboratory, while maize yields were the same in all five treatments. The results caused a minor revolution

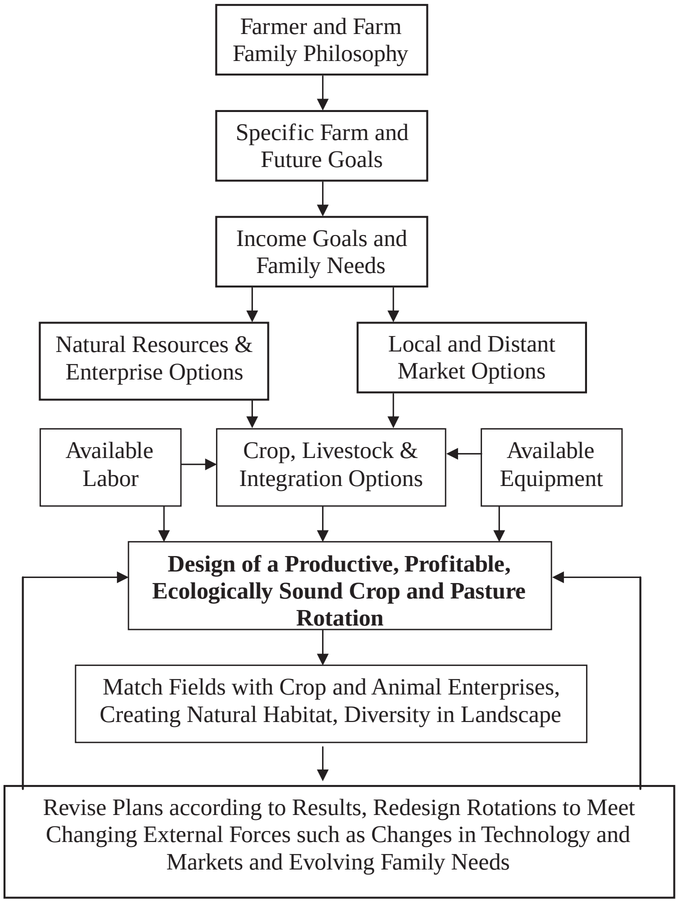

FIG. 1. Flow chart of planning decisions for sustainable field and farm rotations (inspired by Johnson and Toensmeier, 2009).

in the soil testing community, and now there are more rational recommendations from most laboratories that are based on crop response and economic return. Current recommendation based on this landmark research as applied in a pragmatic economic approach are provided by Nebraska Extension (Hergert, 2009).

Another major advance toward fine-tuning nitrogen application rates was the late spring test developed by the late Dr. Fred Blackmer (Blackmer *et al.*, 1989). Soil cores 12 inches deep are taken and samples analyzed for available nitrate, and additional applications made as needed (Creswell and Edwards, 2001). This practice was reported to reduce N applications by Iowa farmers on average 50 kg/ha, saving both production costs and reducing pollution to ground and surface waters. This is especially important when applied manure is part of the fertility program, and it is difficult to predict how much N will be released each year due to effects of temperature and soil moisture. Further refinement of N and other nutrient needs and how to provide for them efficiently with chemical fertilizers is a subject of current research. Variable rate application potentials of new equipment make possible the use of GPS-driven systems that can correlate yield maps with nutrient needs.

These are high-tech strategies to determine nutrient application rates in chemical agriculture, but there was substantial research conducted on substitution-type alternatives early in the last century. Prof. William Albrecht of University of Missouri (Walters and Albrecht, 1996) was a pioneer in seeking alternative methods of providing nutrients to plants. His early work on use of cover crops, manure, and rotations could have easily set the standard for an ecologically-based soil fertility management strategy for major crops in the United States. Yet after the Second World War the rapid expansion of nitrogen fertilizer production drove the system in another direction. Much of Albrecht's research is cited today as one of the foundations for organic farming practices to maintain soil fertility.

One further example of improving efficiency in conventional systems comes from the on-farm research by Ed Penas of University of Nebraska, who compared large plots with applied starter fertilizer to those without (Hergert and Wortmann, 2006). Working with farmers, he found that often starter fertilizers provided a profound visible effect on crop appearance in the early stages, but in only about ten percent of these fields were there economic increases in crop yields. Starter fertilizer was effective only in those fields and years where a cool spring retarded P release, in sandy soils with low organic matter, in soils with low P levels, and in some high pH soils. The additional low addition of nutrients at planting was valuable to get the crop started. In most cases, however, starter fertilizers were only an added expense to the farmer, one that did not pay off economically at harvest.

Substitution of other nutrient strategies for applied chemical fertilizers or choice of less expensive products are two ways that conventional farmers reduce costs in cereal production. The move from granular fertilizer to urea and anhydrous ammonia over several decades is a clear example of this type of substitution. The liquid sources of N are both more concentrated and more easily applied, thus saving material, application, and labor costs (Ebelhar *et al.*, 2007). These strategies can be coupled with accurate soil tests and cautious interpretation of results into lower application rates to reduce costs in conventional systems.

Most often used in organic systems or those in which crop and animal enterprises complement each other on the same farm are applications of composted or raw manure. About half of the applied soluble nutrients in either compost or manure is available in the first year after application, and as a general guide half of what remains is available in the succeeding year (Magdoff and van Es, 2009). Use of on-farm or nearby sources of nutrients is an excellent strategy for substitution for purchased fertilizers if manure is available from livestock or poultry, yet separation of animal production from crop production in most Midwest farms precludes this potential for integration.

In conventional systems, one of the practices used to reduce inputs or to make more efficient use of available fertilizer or water is to substitute one crop for another or a new cultivar for an older one. Before the Green Revolution in rice in Asia, there was limited chemical fertilizer applied to rice because the tall

Oryza indica varieties produced excessive vegetative growth and lodged before harvest. Crosses with the much shorter *O. japonica* varieties produced new cultivars such as IR-8 and its successors that would respond with higher grain production and less lodging (Evans, 1998). Farmers substituted both a new variety for traditional ones and a new chemical fertilizer strategy for one formerly based on local, biological sources. This is an obvious cultivar by fertilizer interaction and a useful emergent property of the new system. This strategy is widely used in production of semi-dwarf wheat and other cereals that respond to N fertilizer with higher grain yields, and not excessive vegetative growth.

Grain sorghum production area increased and the crop replaced maize in Nebraska for several decades in the past century due to its perceived resistance to drought and better water use efficiency. Maximum area in sorghum was 800,000 ha in the 1970s. As irrigation expanded and maize breeders incorporated better drought tolerance into new hybrids, many fields shifted back to maize, and today there are 100,000 ha of sorghum in the state. Maize also has traditionally enjoyed a 5–10% higher market price, and is an easier crop to handle. This change represents a crop species by available water interaction that is also influenced by economics, farmer preference, and large investments in research.

Substitution strategies for nutrient management in organic and sustainable systems include use of compost and manure, introduction of non-traditional soil amendments, and incorporation of other practices such as cover crops and rotations that are discussed in the section on redesign of systems. Application of composted manure and other organic nutrient sources is central to most organic farming operations. For maximum preservation of nutrients, these materials should be incorporated in the field soon after application. Contact with soil organisms and access to moisture are increased by working the compost into the soil, and there is more rapid release of available nutrients for crops. Raw manure may also be applied in organic systems, but this should be either injected in slurry form or incorporated as soon as possible to preserve nutrients for crop use. The organic certification rules state that no root crop can be harvested from fields where manure was applied for a period of 120 days (Gold, 2007). Although manure and compost are preferred sources of soil fertility, if animals are not part of the farming operation this resource could be expensive if the hauling distance adds too much to the price of nutrients.

There is a wide range of nontraditional soil amendments available for organic farmers to maintain soil nutrient status. The testimonials are convincing, and some research data are available to show the positive results of application. In general, there are more of the former, and most soil scientists are hesitant to invest much time in research on these products. In an early report from Rodale Institute (McAllister, 1983) there was a comparison of 20 such products in maize production in southeast Pennsylvania. Several of the materials produced visible changes including greener foliage, and a few actually increased yields. The conclusions from the study, conducted by researchers dedicated to organic farming, were that none of the products was harmful to the crop, but none provided an economic return that would justify their application. Today these are mostly considered very expensive soil nutrients, although there are strong proponents of such products.

Redesign of farming systems to incorporate more complex rotations, green manures, intercropping practices, and other forms of intensification of cycling and resource use is a cornerstone of organic farming. Some of the practices are relevant as well for the conventional farmer. Organic certification rules under the NOP specify that no one crop can follow itself, and there must be at least one legume or sod crop in the rotation. The concept of sequencing unlike species has a number of benefits, whether the rotation includes cereal—legume, row seeded—drilled crop, summer annual—winter annual, or annual—perennial crop. From the fertility and nutrient perspective, each of these patterns provides either a temporal or spatial change in nutrient uptake from the soil. Cereals and legumes have different crop nutrient requirements, and legumes capture and fix nitrogen to provide for most of their own needs plus provide some N for succeeding crops. This depends on amount of N fixed and the removal of N from the field with the harvested crops. For example, much more N is harvested and exported with a soybean crop than can be fixed: about 50 kg/ha of N is removed by a soybean crop that yields 3 t/ha, while the growing soybean crop may only fix 80% of that much N during the season. Compared to a cereal crop such as maize where there could be over 60–70 kg/ha removed with a 10 t/ha crop, the soybean could be considered a "nitrogen sparing" crop (Clegg and Francis, 1993).

Systems that may be both spatially and temporally diverse are discussed further under the sections on crop rotations, crop/animal systems, and future design of farming systems. This includes consideration of permaculture and agroeforestry, as well as perennial polycultures that are envisioned for the prairie landscape.

III. ECOLOGICAL PEST MANAGEMENT

Efficiency of pest management in conventional systems includes a number of features that could be attributed to research in sustainable agriculture, although it is difficult to separate this influence from the drive toward reduced costs. Efficiency depends on careful use of pesticides, choice of cultivars with genetic resistance, and to some degree the use of crop rotations for insect, weed, crop pathogen, and other pest control. There are many potential ways to reduce costs by increasing pest management efficiency, especially through careful crop scouting and adherence to integrated pest management (IPM) strategies. IPM is one cornerstone of sustainable agriculture, and much of the important work in California and elsewhere predated the current drive toward greater sustainability.

Improved efficiency can be gained by reducing rates or number of applications when possible, rotating pesticide chemistry, and careful use of economic thresholds in making management decisions. Reduced rates provide a rational way to lower costs and potential environmental impacts, and they are based on the assumption that chemical companies are conservative in recommending high enough rates that are certain to control a given weed situation or prevalent insect or pathogen. There is a cost saving to the farmer in reduced product costs, although application costs remain fixed. The disadvantages are that the product may not work, and any guarantee by the supplier will be negated by farmers not following label instructions. Yet this strategy could be considered a transition step toward eliminating the chemical pesticide in a more sustainable system.

Number of applications of pesticides can be reduced by careful scouting of fields and monitoring of pests. An important part of IPM is the economic threshold concept, where a control method is not applied unless a specific pest reaches the point where the control costs will be more than returned by increased production. WeedSOFT is an example of a computer program for weed management decisions that was developed by University of Nebraska Extension (http://weedsoft.unl.edu/ (accessed October 26 2009). A comprehensive web site that provides up-to-date scouting information for the Midwest has been compiled by Extension Specialist Bob Wright at University of Nebraska (http://entomology.unl.edu/fldcrops/ipm/insects.htm, accessed September 16, 2009). This includes numerous guides for managing irrigation, insects, pathogens, weeds, and soil fertility, as well as providing pesticide safety information. It is noteworthy that this was assembled by an entomologist steeped in IPM, an early strategy for production sustainability.

Growing numbers of pest species that are resistant to chemical control present new challenges to farmers and researchers. Proponents of organic farming maintain that reduced rates and fewer chemical applications will lower the pressure on pests to mutate and develop resistance to pesticides. Requirements for use of non-GMO hybrids of maize in a small refuge section of each field represent one strategy to maintain a wild population of insects, thus slowing the march toward resistance. On the other side, chemical control proponents argue that reduced rates will not manage insects properly and will allow more to escape and develop resistance. The debate continues.

Substitution of resistant crop hybrids or varieties is one strategy employed to reduce pest populations and crop damage, used by both conventional and organic farmers. The growing organic farming segment has created an increased demand for genetic resistance, especially for insects and pathogens. The latter is especially important since the fungicide treatment of seed is not allowed in organic systems. This is an example of how an increase in organic farming will spur development of new cultivars that will also benefit conventional farmers. The major difference is that conventional farmers can depend on transgenic technology for pest resistance, while this is not allowed in certified organic systems.

A large issue for organic farmers is the substitution of transgenic hybrids, for example maize and cotton with incorporated *Bacillus thuringiensis* (Bt), for chemical methods of insect control. With the wide deployment of new hybrids that include this trait, there is an inevitable result of insect resistance and loss of this tool for organic farmers. Because of developing resistance, chemical companies are trying to develop other incorporated biological agents for insect control, but progress has been slow. This is analogous to development of several different types of chemistry for weed control, so that a farmer can use different herbicide modes of action in a rotation of chemicals, and this should drastically slow the shifts in weed species resistance or tolerance to herbicides.

Substitution in organic systems includes use of non-chemical products, changes in planting date and other practices, and choice of highly competitive crops and varieties, plus appropriate crop rotations. All of these strategies are available to conventional farmers, and all provide economically useful methods except for the use of often expensive non-chemical products. The increased value of organic products through premiums in the marketplace, an option not available to conventional farmers, may offset the higher costs of pest management in organic systems.

Systems redesign to eliminate need for outside inputs is the most desirable alternative, and is the strategy often used by organic or sustainable farmers. Increasing biodiversity, both temporally through crop rotations and spatially through multiple species plantings, represents a vital component of how organic farmers think about pest management. Greater sustainability in production can be achieved by using thoughtful design of crop rotations that can reduce pest populations or spread of pests across the landscape. Rotations of unlike species are discussed in the next section, and represent one way to keep changing the field habitat in order to reduce opportunity for pests to reproduce and spread. At least a three-year rotation is needed to suppress populations of maize rootworm (*Diabrotica* spp.) since there has been development of an extended diapause in the insect that makes a two-year rotation ineffective in some areas. A seven-year rotation before returning to another potato crop is recommended to control *Streptomyces* spp. that causes potato scab disease. These practices are available to conventional farmers as well.

One unique strategy of spatial rotation in conventional cotton growing is found in Colombia, where there are two growing seasons and two different regions that are appropriate for cotton. By national agreement with the cotton farmers, the crop is planted in the Cauca Valley in southwest Colombia in the first rainy season each year, and on the north coast some 600 km away in the second rainy season. This spatial separation prevents or at least reduces the spread of insects from one field to another, and in the high temperature of a tropical climate assures that pests will not survive until the following season.

Spatial diversity includes use of multiple species systems or highly diverse combinations such as permaculture or perennial polycultures, strategies to keep pest populations below the economic threshold. The concept is to confront the insect or pathogen with a diverse array of vegetation, most of which is not desirable for feeding and reproduction, thus slowing the pest population increase and spread. Strip cropping of maize, soybean, and winter cereal is one example for temperate zone application of this principle. Coupled with a rotation of the crops in strips, this strategy creates biodiversity in both time and space. Permacultures described by Mollison (1990) and perennial polycultures being developed at The Land Institute (Jackson, 1980; Soule and Piper, 1993) represent methods of creating a permanent cover over the land that will suppress weeds, and give priority to the crops of interest for economic gain or ecosystem services. Maintaining diversity in the hedgerows, windbreaks, and roadsides around fields provides another method of creating habitat for beneficial predators and parasites, and thus a non-chemical method of pest management. These strategies generally are not available to the large, conventional farmer since they depend on smaller field units and more complicated management. The strategy of weed management through use of "many small hammers," a combination of control methods used across the farm and landscape, has been proposed by Liebman and Davis (2009) as a more durable method of suppressing unwanted vegetation than those that use single strategies such as herbicides or tillage alone. This is available to all farmers, a strategy to make conventional farming more sustainable.

IV. CROP ROTATIONS

Efficiency of crop rotation in conventional system has been obscured by input substitution. In an era of agricultural specialization, one might expect that conventional systems would evolve to the simplest form possible: growing one crop year after year. In general, that has not occurred. It can be argued that the practice of crop rotation came about by necessity (Porter, 2009). Farmers found that they could increase crop yields on a given piece of land if they changed the crops grown there over time. The first documented evidence of the benefits of crop rotation is over 2,000 years old, when it was recorded that including certain crops, now known as legumes, in a rotation benefited other subsequent crops. As with the origin of crop domestication, there is good reason to believe that the practice of crop rotation evolved independently in different regions of the world. This evolution occurred principally through trial and error. Just as certain crops are best adapted to certain environments and growing conditions, associated crop rotations are likewise site specific. For example, the four-year Norfolk rotation, which consisted of wheat (*Triticum* spp.)-turnip (*Brassica rapa*)-barley (*Hordeum vulgare*)-red clover (*Trifolium pretense*), contributed to more than doubling wheat yields in England in the 1700s (Pearson, 1967). That combination of crops, however, could not be grown in the lowland tropics.

In the upper Midwest, the breadbasket of the U.S., maize (*Zea mays*) and small grains including wheat dominated the planted areas along with fallow and pasture from the start of arable agriculture in the prairie. This system changed when adoption of diesel equipment replaced the need for animal traction. This coincided with the rapid adoption of soybean (*Glycine max*), and today the predominant crops grown in the region are maize rotated annually with soybean, a grass with a legume. About the same time synthetic fertilizer, herbicide, and fungicide use became more commonplace, which led to the conventional agriculture we know today.

Today, maize and soybean production is so pervasive in the upper Midwest that in some counties well over 75% of the total land area of the county is planted to one of these crops (Porter, 2009), leaving little area for other crops or livestock alternatives.

Substitution with synthetic fertilizers, herbicides, and fungicides led to a belief that the need for crop rotation would disappear as farmers controlled yield-limiting factors such as fertility, erosion, and weed competition, thereby mitigating the necessity for crop rotations (Melsted, 1954). Eliminating the need for crop rotation without compromising production has been more challenging than anticipated. Today yield increases associated with crop rotation, referred to as the *rotation effect* (Pierce and Rice, 1988) and *monoculture yield declines* (Sumner *et al.*, 1990) are not fully understood. Thus, the common maize—soybean rotation rather than continuous corn or continuous soybean is a result of conventional farmers gaining efficiency from such a practice. This two-crop rotation also allowed for an overall gain in nitrogen use efficiency and a reduction in weed problems resulting from a sequencing of different herbicide families used on each crop.

Daberkow and Gill (1989) estimated that only 5 to 10 rotations were being used on over 80% of the cropland in the United States, and they typically involve only two crops in the rotation. These include the maize–soybean rotation in the upper Midwest; soybean rotated in a double cropping system with winter wheat in the Piedmont and lower Midwest and Eastern Upland Region; wheat and wheat–fallow rotation in the northern Great Plains; and rice (*Oryzae sativa*)–soybean rotation in the Mississippi Delta Region.

Today, widespread use of synthetic fertilizers and pesticides dominates current agricultural practices in industrialized countries. Yet these inputs mask the true benefit of crop rotation (Porter *et al*., 2003). In contrast, organic farmers are reliant on crop rotation and this practice is one of the foundations of the organic cropping system. Many useful articles have been written on crop rotations for conventional systems (Daberkow and Gill, 1989; Karlen *et al*., 1994) and for organic and sustainable production systems (Francis and Clegg, 1990; Kuepper and Gegner, 2004; Magdoff and Van Es, 2009). The benefits of including well-managed cover crops in the crop rotation have been described in detail (Sustainable Agriculture Network, 2007). *Substitution* of NOP-approved products for an adequate crop rotation can also be implemented in organic production systems. Some organic producers have a "silver bullet" mentality, thinking they can avoid the negative effects of an inefficient crop rotation through NOP and OMRI approved organic inputs. Input substitution using NOP-approved nitrogen fertilizers, herbicides, and insecticides could be avoided by adding more legumes in the crop sequence, introducing a more efficient rotation, and increasing areas in wild field boundaries for beneficial insects.

System redesign of the crop rotation in conventional systems may begin as simply as adding an 'off-season' cover crop to the rotations, and thus not impacting or minimally impacting the typical cash crops. Or in a sequence, systems redesign may radically alter the crops grown and expand the number of crops, and thus the length of the crop rotation. System redesign of a crop rotation in organic cropping systems could include the adoption of improved, multifunctional crop rotations that enable enhanced and more sustainable ecosystem function and increase profitability. Choice of crops with available markets and favorable prices could include introduction of more perennial crops across multiple, varied, and large watersheds. Use of perennial forages could enhance the reintegration of crops and livestock on the farm. A move toward reduced tillage and crop diversification could also prove positive. Such systems redesign could provide greater farming system resilience, enhanced income stability, and multiple benefits for society such as provision of ecosystem services. Most of these changes could be introduced into conventional agricultural systems, providing many of the same benefits.

V. CROP/ANIMAL SYSTEMS

As described above in several examples, the ultimate transition of current systems to more sustainable alternatives involves redesign of the farming system. The biological foundations for redesign can be found in writings by Steiner, Albrecht, Howard, Balfour, and others with their focus on design and management of whole systems. Potential to integrate principles of biodiversity, resilience, and long-term durability under changing and more variable climate is greatly enhanced by the integration of crops and animals on farms.

Martin Entz and Joanne Thiessen Martens (2009) describe the development of managed crop/animal systems 8000 to 10000 years BP. Scientists in western Canada observed more than 100 years ago that greater permanence could be achieved through mixed farming (Janzen, 2001). System sustainability has been associated with crop/livestock integration in the Nordic Region (Granstedt, 2000). The separation of livestock and crops on different farms has come to be called "the disintegration of agriculture" (Clark and Poincelot, 1996). And Schiere *et al.* (2002) conclude that reduced crop/livestock integration correlates closely with increased need for fossil fuel use in agricultural systems.

Through applying principles of agroecology, it is obvious that a functional integration of crops and animals to enhance nutrient cycling and increase spatial biodiversity is more important than merely producing crops and livestock on the same farm (Clark and Poincelot, 1996). Diversification alone can add economic resilience to the product mix on a farm, but this does not require dependence of one enterprise on another. As the distance between source of an input (e.g., animal manure) and the place it will be applied (e.g., crop field) increases, there is an increasing cost of labor and energy costs involved in the system (Schiere *et al.*, 2002).

Finally, crop/animal integration can be central to providing ecosystem services from agriculture, especially from organic agriculture. For example, more forages in the system and especially perennial species and mixtures of species can add biodiversity, provide year-round cover that will prevent soil erosion, enhance nutrient cycling especially if the forages are grazed, and increase accumulation of soil organic matter (Clark, 2009). A sequence that includes semi-permanent or permanent cover can enhance water capture and storage, sequester carbon, and improve water quality in the nearby waterways and the groundwater. These emergent properties make essential contributions to health of soil and the landscape as well as the agroecosystem, but are rarely rewarded in the contemporary marketplace.

VI. CONCLUSIONS: FUTURE DIRECTIONS FOR ECOLOGICALLY SOUND FARMING

Sustainable systems are differentiated from conventional systems by focus on more than just production and economics, plus minimally meeting environmental regulations in the most cost-effective way. Sustainability means preserving economic productivity while taking seriously the ecological foundation and social implications and impacts of farming. It includes designing systems that are resilient and can endure for the indefinite future. A summary table of strategies and practices that are commonly found in conventional and in emerging sustainable systems was presented in the introduction. The comparisons are stated in rather extreme terms, in order to clearly distinguish between two philosophies and farming systems. In fact, most farms employ some combination of these strategies, and many fall on a spectrum between the extremes.

Farmers managing their systems following conventional, "sustainable," organic, or other philosophies or strategies are seeking to improve the profitability and long-term durability of production, as well as comply with regulations and preserve the value of their land resource. We have described how farmers use increased efficiency of input use, substitution of less costly or more effective cultivars or other inputs, and redesign of systems to help meet their goals. It is our observation that conventional farmers generally use the strategies of increasing efficiency and at times substituting inputs, while organic and other sustainable farmers use primarily substitution and redesign of systems. What is intriguing yet difficult to determine is the impact of research and extension work in organic farming, limited as it has been, on the decisions made by conventional farmers to make their systems more environmentally sound and profitable. This is a potentially fruitful area for research.

We conclude that ecology is an essential and integral organizing principle in organic farming, and concepts from ecology

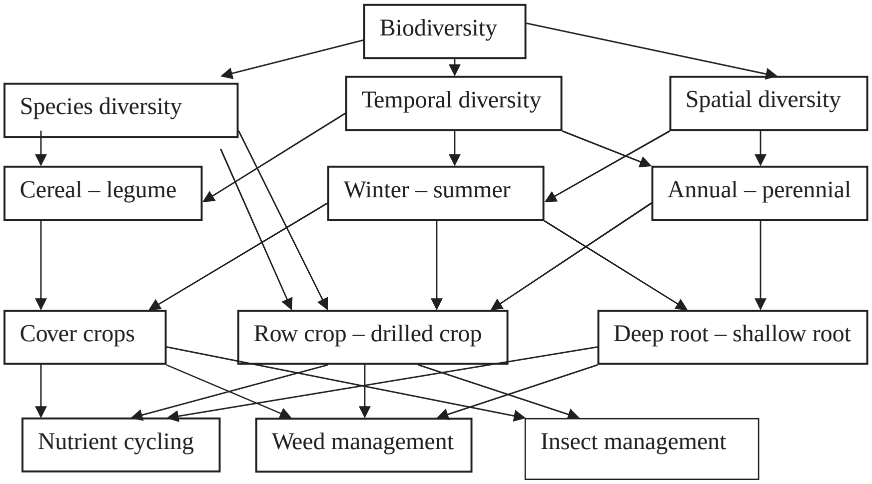

FIG. 2. Ecological principle of biodiversity expressed in practices for design of sustainable crop rotations and systems, illustrating major interactions and consequences.

are gradually finding their way into conventional agriculture (Drinkwater, 2009). One indicator of the traction these terms have—ecology and sustainability—is the increasing frequency of their use by input providers who advertise their products "to create a more sustainable and profitable farming system." This was not the case even a decade ago. With increasing concern about the long-term impacts of agricultural inputs on waterways and the growth of dead zones in a number of places where rivers discharge into the oceans of the world, there are likely to be more regulation and greater incentives to reduce these problems at the source. With environmental soundness as an additional incentive, conventional farmers are likely to look to alternative systems and principles of ecology for design of future systems.

A number of specific practices used in organic and sustainable farming provide examples of the application of ecology to practical farming systems. A simplified diagram that includes some of the major ecological factors that go into design of systems, and how they impact nutrient cycling, weed management, and insect management is provided in Figure 2. The primary factors and their interactions have been described in several of the above sections, and an excellent conceptual summary is provided by Drinkwater (2009).

To meet the needs of current citizens without reducing the potential for future generations to also meet their needs requires careful thought and evaluation of current systems. We have potential to increase efficiency of agriculture, to substitute less costly or more environmentally sound inputs or practices, and to redesign systems to create greater productivity as well as resilience in agroecosystems. Many of the changes needed are based on principles of ecology, and on the study of the stability and durability of the natural prairie in this region. Organic and sustainable farmers have learned these lessons, and there is an increasing application of their methods to what we call conventional farming. Dynamic change will always be a part of agriculture, and those farmers and researchers who are on the cutting edge of system design and using multiple criteria to evaluate success will continue to provide models of agroecosystems that can help sustain the human species as well as a healthy natural environment into the future.

REFERENCES

Aldridge, S. 2008. *Insect resistance: from mechanisms to management*. Assoc. British Sci. Writers, http://www.absw.org.uk/Briefings/insecticide_resistance.htm Accessed July 2, 2009.

Altieri, M. A., and Nicholls, C. I. 2005. *Manage Insects on Your Farm: A Guide to Ecological Strategies*. Handbook Series Book 7, Sustain. Agric. Res. Educ., U.S.D.A., Washington, D.C.

Bird, G. W., Grieshop, M., Hepperly, P., and Moyer, J. 2009. Climbing Mt. Organic: An ecosystem approach to pest management. **In**: *Organic Farming: The Ecological System.* pp. 197–216. Francis, C. A., Ed., Agron. Monograph 54, Amer. Soc. Agron., Madison, Wisconsin.

Blackmer, A. M., Pottker, D., Cerrato, M. E., and Webb, J. 1989. Correlations between soil nitrate concentrations in late spring and corn yields in Iowa. *J. Prod. Agric.* **2:** 103–109.

Clark, A. (Ed.). 2007. *Managing Cover Crops Profitably.* 3rd edition. Handbook Series Book 9, Sustain. Agric. Res. Educ., U.S.D.A., Washington, D.C.

Clark, E. A. 2009. Forages in ecologically-designed organic crop/animal systems. **In**: *Organic Farming: The Ecological System.* pp. 85–112. Francis, C. A., Ed., Agron. Monograph 54, Amer. Soc. Agron., Madison, Wisconsin.

Clark, E. A., and Poincelot, R. (Eds.) 1996. The contributions of managed grasslands to sustainable agriculture in the Great Lakes Basin. *J. Sustain. Agric.* **8(2/3):** 1–172.

Clegg, M. D., and Francis, C. A. 1993. Crop management. **In**: *Sustainable Agriculture Systems.* pp. 135–156. Hatfield, J. L., and Karlen, D. L., Eds., Lewis Publ., Chelsea, Michigan.

Creswell, J., and Edwards, E. 2001. Late spring nitrogen test can help manage nitrogen applications. PM 1714, *Iowa State Univ. Extension*, http://www.extension.iastate.edu/Publications/PM1714.pdf. Accessed 11 September 2009.

Daberkow, M., and Gill, S. 1989. Common crop rotations among major field crops. **In**: *Agricultural Resources: Inputs Situation and Outlook Report.* pp. 34–40. AR-15. Econonlic Research Service, USDA, Washington, D.C.

Drinkwater, L. E. 2009. Ecological knowledge: foundation for sustainable organic agriculture. **In**: *Organic Farming: The Ecological System.* pp. 19–50.

Francis, C. A., Ed., Agron. Monograph 54, Amer. Soc. Agron., Madison, Wisconsin.

Ebelhar, S. A., Hart, C. D.. Hernandez, J. D., Paul, L. E., and Warren, J. J. 2007. Evaluation of new nitrogen fertilizer technologies for corn. *Illinois Fertilizer Conf. Proc*., pp. 64–71. Nafziger, E. D. Ed., Illinois Cooperative Extension, Univ. Illinois, Urbana, Illinois.

Entz, M., and Thiessen Martens, J. R. 2009. Organic crop-livestock systems. **In**: *Organic Farming: The Ecological System.* pp. 69–84. Francis, C. A. Ed., Agron. Monograph 54, Amer. Soc. Agron., Madison, Wisconsin.

Evans, L. T. 1998. *Feeding Ten Billion: Plant and Population Growth*. Cambridge Univ. Press, Cambridge, U.K.

Francis, C., and Hodges, L. 2009. Human ecology in future organic farming and food systems. **In**: *Organic Farming: The Ecological System.* pp. 301–324. Francis, C. A. Ed., Agron. Monograph 54, Amer. Soc. Agronomy, Madison, Wisconsin.

Francis, C., Jordan, N., Porter, P., Breland, T. A., Lieblein, G., Salomonsson, L., Sriskandarajah, N., Wiedenhoeft, M., DeHaan, R., Braden, I., and Langer, V. 2011. Innovative education in agroecology: Experiential learning for a sustainable agriculture. *CRC Crit. Rev. Plant Sci.*. [this issue]

Francis, C., Lieblein, G., Gliessman, S., Breland, T. A., Creamer, N., Harwood, R., Salomonsson, L., Helenius, J., Rickerl, D., Salvador, R., Wiedenhoeft, M., Simmons, S., Allen, P., Altieri, M., Flora, C., and Poincelot, R. 2003. Agroecology: The ecology of food systems. *J. Sustain. Agric*. **22**(3): 99–118.

Francis, C. A., Poincelot, R., and Bird, G. M. Eds. 2006. *Developing and Extending Sustainable Agriculture: A New Social Contract*. Haworth Press, Binghampton, New York.

Gliessman, S. R. 2007. *Agroecology: The Ecology of Sustainable Food Systems*. CRC Press, Taylor and Francis, New York.

Gold, M.V. 2009. *Organic certification: National Organic Program.* USDA, Washington, DC. http://www.nal.usda.gov/afsic/pubs/ofp/ofp.shtml Accessed 29 October, 2009.

Hergert, G. W. 2009. *Soil Testing More Important Than Ever for Efficient Fertilizer Use*. Nebraska Extension, Univ. Nebraska — Lincoln. http://panhandle.unl.edu/web/panhandlerec/meeting_challenge_2 Accessed 29 October, 2009.

Hergert, G., and Wortmann, C. 2006. *Using Starter Fertilizer for Corn, Grain Sorghum, and Soybeans*. G361, Nebraska Extension, University of Nebraska — Lincoln. http://www.ianrpubs.unl.edu/epublic/pages/publicationD.jsp?publicationId=570 Accessed 12 September 2009.

Jackson, W. 1980. *New Roots for Agriculture*. Univ. Nebraska Press, Lincoln, Nebraska.

Janzen, H. H. 2001. Soil science on the Canadian prairies — peering into the future from a century ago. *Can. J. Plant Sci*. **81:** 489–503.

Karlen, D. L., Varvel, G. E., Bullock, D. G., and Cruse, R. M. 1994. Crops rotations for the 21st century. *Adv. Agron*. **53:** 1–45.

Kirschenmann, F. 2009. Farming in the middle: an ethical imperative. *Ch. 15 in: Organic Farming: The Ecological System.* pp. 325–342. Francis, C. A., Ed., Agron. Monograph 54, Amer. Soc. Agronomy, Madison, Wisconsin.

Kuepper, G., and Gegner, L. 2004. An overview of organic crop production: Planned crop rotation. ATTRA(Appropriate Technology Transfer for Rural Areas) Publication #IP170. http://attra.ncat.org/attra-pub/organiccrop/tools2.html Accessed October 26, 2009.

Liebman, M., and Davis, A. S. 2009. Managing weeds in organic farming systems: An ecological approach. **In**: *Organic Farming: The Ecological System.* pp. 173–196. Francis, C. A., Ed., Agron. Monograph 54, Amer. Soc. Agron., Madison, Wisconsin.

MacRae, R. J., Hill, S. B., Mehuys, G. R., and Henning, J. 1990. Farm-scale agronomic and economic transition to sustainable agriculture. *Adv. Agron*. **43:** 155–198.

Magdoff, F., and van Es, H. 2009. *Building Soils for Better Crops. 3rd Ed.* Sustain. Agric. Res. Educ., U.S.D.A., Washington, D.C.

McAllister, J. 1983. *A Practical Guide to Novel Soil Amendments*. Rodale Research Center, Emmaus, Pennsylvania.

Meffe, G., Neilson, L., Knight, R. L., and Schenborn, D. 2002. *Ecosystem Management: Adaptive, Community-Based Conservation*. Island Press, Washington, D.C.

Melsted, S. W. 1954. New concepts of management of Corn Belt soils. *Adv. Agron*. **6:** 121–142.

Mollison, B. 1990. *Permaculture*. Island Press, Washington, D.C.

Murphy, G. 2001. *The Constitution of the Iroquois Nations: The Great Binding Law, Gayanashagowa*. Cleveland Free-Net - aa300, Cybercasting Services Division, National Public Telecomputing Network (NPTN), October 1, 2001.

National Research Council. 2003. *Frontiers in Agricultural Research: Food, Health, Environment, and Communities*. National Academies Press, Washington, D.C.

Pearson, L. C. 1967. *Principles of Agronomy.* Reinhold Publ. Corp., New York.

Pierce, J. J., and Rice, C. W. 1988. Crop rotation and its impact on efficiency of water and nitrogen use. **In**: *Cropping Strategies for Efficient Use of Water and Nitrogen.* pp. 21–42. Hargrove, W. L., Ed., ASA Spec. Publ. 51. Amer. Soc. Agron., Madison, Wisconsin.

Schiere, J. B., Ibrahim, M. N. M., and van Kaulen, H. 2002. The role of livestock for sustainability in mixed farming: criteria and scenario studies under varying resource allocation. *Agri., Ecosys. Environ*. **90:** 139–153.

Soule, J. D., and Piper, J. K. 1992. *Farming in Nature's Image: An Ecological Approach to Agriculture.* Island Press, Washington, D.C.

Sumner, D. R., Gascho, G. J., Johnson, A. W., Hood, J. E., and Treadgill, E. D. 1990. Root diseases, populations of soil fungi, and yield decline in continuous double-crop corn. *Plant Dis.* **74:** 704–710.

Sustainable Agriculture Network. 2007. *Managing Cover Crops Profitably, 3rd Ed.* Sustain. Agric. Res. Educ. Progr., U.S.D.A., Washington, D.C.

Walters, C. Ed., and Albrecht, W. A. 1996. *The Albrecht Papers*. ACRES International, Metairie, Louisiana.

WCED (World Council on Economic Development). 1988. *Our Common Future*. World Council on Economic Development, Oxford Univ. Press, Oxford, U.K.

Weed Science Society of America. 2008. *International Survey of Herbicide Resistant Weeds*. http://www.weedscience.org/in.asp Accessed July 12, 2009.

White, G., and Maze., J. 1995. *Henry A. Wallace: His Search for a New World Order*. Univ. North Carolina Press, Chapel Hill, NC.

Critical Reviews in Plant Sciences, 30:74–94, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554354

Pest Control in Agro-ecosystems: An Ecological Approach

George Ekström[1] and Barbara Ekbom[2]
[1]*Former Pesticide Regulator, Uppsala, Sweden*
[2]*Professor of Entomology, Department of Ecology, Swedish University of Agricultural Sciences, P.O. Box 7044, SE-750 07 Uppsala, Sweden*

Table of Contents

Address correspondence to Barbara Ekbom, Professor of Entomology, Department of Ecology, Swedish University of Agricultural Sciences, P.O. Box 7044, SE-750 07 Uppsala, Sweden. E-mail: Barbara.Ekbom@slu.se

Referee: Prof. Ivette Perfecto, School of Natural Resources and Environment, Dept. of Natural Resources, University of Michigan, 440 Church St., Ann Arbor, MI.

This text combines two basically different views on pest control namely the scientific researcher's view on pest control and the pesticide regulator's views on pesticide control aiming at a common and pragmatic ecological approach. A set of practicable 'tools' are discussed that can be used to monitor and reduce environmental impact on agro-ecosystems where the ultimate goal is to move towards a more environmentally sustainable agriculture. General principles governing farming systems and pest control strategies are illustrated with pesticide use and pesticide risk reduction measures in coffee and rice cultivations. Adaptive pest control based on Integrated Pest Management with a rational use of pesticides as a last resort is suggested to be the most viable way forward.

Keywords adaptive pest control, agricultural performance indicators, climate field schools, continuous improvement, environmental impact quotients, impact reduction, rational pesticide use, resilience

I. FROM IMPACT REDUCTION TO ECOLOGICAL APPROACH

In the realm of plant protection modern agriculture has long relied on artificial inputs such as pesticides. The use of pesticides was easily integrated into modern agricultural management. Sprays could be scheduled or used as a response to high numbers of invading insects, high levels of plant disease or high occurrence of weeds. The use of pesticides in prophylactic manner or in response to perceived attack is basically uncomplicated.

It was not long before it became clear that the use of pesticides had negative aspects (Carson, 1962), not only of an environmental character, but also in terms of efficacy. Insect, diseases, and weeds have shown a remarkable ability to adapt and become resistant to pesticides; making the development of new pesticides a requirement for continued use as a management technique. In addition, detrimental effects to natural enemies sometimes caused resurgence of pest attacks when the effects of chemicals abated. Another problem can be that when serious target pests are eliminated secondary pests, previously suppressed by natural enemies or competition from the main pest, may gain increased pest status. Although pesticides can remove the threat of plant attack it is not always an economically sound strategy. The yield gained by removing plant attackers does not always pay for the costs of a pesticide treatment. In addition concerns about human health, both for those using the pesticides and those that might consume them on food products, are not negligible. Millions of cases of acute poisoning from pesticides have been estimated to occur annually and chronic effects due to, for example, endocrine disruptions have been recognized (Richter and Chlamtac, 2002). Children are at greater risk than adults from pesticides because of their small size and greater exposure rates (UNEP, 2004).

As a response to these problems, especially when dealing with insect pests, economic or treatment thresholds were introduced. The reasoning was that the costs of the treatment should be recovered in terms of yield or the treatment should not be performed. Pesticides would most likely not be used to the same extent as when following a spraying schedule or in response to perceived risk. This added a degree of complexity to pesticide use. Monitoring of pest and disease levels in the field is necessary to determine when economic thresholds are reached. Determination of economic thresholds is not a simple process and thresholds are not available for all crops and all potential pests and diseases limiting the number of situations where the threshold approach can be used.

It has been 50 years since an influential paper on the integration of chemical and biological control expounded the importance of considering the entire ecosystem when designing good pest control (Stern *et al*., 1959). Although the term "ecosystem service" was not used at that time the importance of natural control and biological control was recognized. Human culpability in increasing pest problems was also highlighted in terms of changing and manipulating ecosystems in such a way that certain species are favoured and can become pests. This call for integration of biological and chemical methods of pest control was one of the early steps in introducing an ecological perspective to pest management within conventional agriculture.

In 1992, the United Nations Conference on Environment and Development concluded that:

- Chemical control of agricultural pests dominated the scene;
- Overuse of pesticides had adverse effects on farm budgets, human health and the environment, as well as on international trade;
- Integrated Pest Management (IPM)—combining biological control, host plant resistance and appropriate farming practices and minimizing the use of pesticides—is the best option for the future;
- IPM guarantees yields, reduces costs, is environmentally friendly and contributes to the sustainability of agriculture;

- IPM, therefore, should go hand in hand with appropriate pesticide management to allow for pesticide regulation and control, including trade, and for the safe handling and disposal of pesticides, particularly those that are toxic and persistent (UNCED, 1992).

Some characteristics of modern, conventional agriculture that have bearing on pest outbreaks are loss of diversity and frequent disturbance within the system (Landis *et al*., 2000). Loss of diversity can be described in very broad terms. First of all growing crops in monoculture and removing weeds decreases the vegetation diversity both in terms of species and structure, there is usually only one height of vegetation (Shennan *et al.*, 2005). Crops are often cultivars with little genetic diversity. This profoundly reduces the possibility of crop adaptation to the environment but promotes increase in attacker virulence, because damaging organisms have only a limited amount of genetic diversity to overcome. Landscape diversity in agricultural areas has declined as labor efficiency has become a priority; mechanization favours large and uniform production units and natural habitats are appropriated as agriculture intensifies. Disturbance occurs repeatedly in agriculture and is often dramatic. This means that there is little scope for species within the system to adapt to their surroundings. Many pests and diseases that frequently cause problems are early successional opportunists. They have evolved to take advantage of simple, regenerating ecosystems after disruption. Species with excellent dispersal ability and rapid growth and reproduction are commonly the pests that are most severe (Tscharntke *et al*., 2005).

Multiple interactions are present in ecosystems. In agriculture there has been a tendency to focus only on plant and attacker when dealing with plant protection. That natural enemies will have an impact on attacker abundance is well-known in the context of biological control. Recognition of other interactions that influence pest abundance is a growing area of research. We know that plants may have an impact on natural enemies by providing cues for the enemies to find pest prey. Changes in plant quality due to fertilization may affect pests and diseases. More recently it has been shown that the action of pests on the plant's aboveground parts may have consequences for the functioning of soil food webs (Dyer and Letourneau, 2003).

Agriculture takes place in time and space (Ekbom, 2000). This adds multiple dimensions to the ecological interactions. A crop's ability to withstand pest attack will be influenced by the surrounding landscape as well as by the vigour and developmental stage of the crop. It is not enough to know only the conditions in the field, the placement of the field in the landscape may determine how fast pest colonization and enemy response may occur. If crop development is rapid and strong, the crop will probably be able to tolerate pest attacks better than late and poorly developed crops.

Although there are no easy solutions several general principles emerge that can guide in the design of future agricultural system for better pest control. Nicholls and Altieri (2007) call for the restoration of agricultural diversity. Increasing species diversity by using different crops combinations varied in time and space; poly-cultures and cover crops are examples of agricultural elements that not only can prevent or reduce pest attack but also can increase soil fertility. Increased cultivation of perennial crops can provide refuges and reservoirs for natural enemies and also facilitate their dispersal into nearby annual crop fields. Diversity at the landscape level should be enhanced by using structurally diverse crops and by creating and maintaining non-crop areas with rich and natural vegetation.

Today there is strong support for the view that there is a need to understand biotic interactions within an ecological framework in order to support crop productivity and environmental health (Shennan, 2008). Integration has moved far beyond a mix of chemical and biological control. Ecosystem management in light of species diversity, disturbance dynamics, and multi-trophic interactions, all considered on multiple spatial and temporal scales, is becoming accepted as an approach to designing more sustainable agriculture. Clearly such an approach is very complex and responses to management changes will not be easy to predict (Shennan, 2008).

For this reason it is essential that future agricultural management strategies are developed together with stakeholders. Our current understanding of the multitude of interactions in the agricultural ecosystem is still rudimentary. Taking steps to reverse negative trends in agriculture will not be easy or straightforward and have to be supported by decision makers as well as users.

II. ASSESSING ECOLOGICAL IMPACT AND MONITORING AGRO-ENVIRONMENTAL PERFORMANCE

It is not a trivial task to assess the health of an ecosystem. In the absence of baseline ecological data and detailed knowledge of ecosystem functions some general assumptions must be made. One such assumption is that the use of pesticides will create an environmental hazard and certain characteristics of the pesticide will determine the severity of that hazard. In the following text we introduce some of the methods currently in use to appraise pesticides and plant protection strategies from an environmental point of view.

A. Environmental Risk Indicators to Monitor Pesticide Reduction in National Programs

Swedish government agencies have used environmental and health risk indicators since 1988 to monitor pesticide reduction. The Swedish pesticide reduction program has achieved a 63% reduction in pesticides sold for use in agriculture and horticulture (from the baseline period 1981-1985 to 2006). From 2002 there is no longer a goal in terms of reduction of quantities sold; instead reduction based on risk indicators is used (Ekström and Bergkvist, 2008). The calculation of the Environmental Risk Indicator (ERI) involves the calculation of an ERI value for every pesticide (active substance) used in agriculture. The calculation includes the following data:

> ERI = annual sold quantity * (1/ recommended dose rate) * (environmental toxicity score + persistence score + bioaccumulation score + mobility score) * application method score for environment exposure * number of spray events * score based on results of surface and ground water monitoring * leaching index.

ERI values for individual pesticides (active substances) are then added together to obtain an overall ERI for agriculture in a particular year. Using this method, the environmental risk from pesticides used in agriculture in Sweden in 2006 was 28% lower when compared to the reference year 1988. In comparison, the health risk, calculated using a similar method, was 69% lower in 2006 compared to 1988 (Bergkvist, 2004; Ekström and Bergkvist, 2008).

B. Percentage of Land Area under Organic Farming to Monitor National Agro-Environmental Performance

The Swedish government has set sixteen national environmental quality objectives with regard to the natural environment, the urban and rural environments, and society at large. Two of the objectives apply to crop protection strategies and pesticide use, namely the ‘Non-toxic Environment’ objective and the ‘Varied Agricultural Landscape’ objective. Three indicators are used to monitor the use of pesticides in agriculture: (1) the level of use and risk scores of plant protection products based on sales statistics, (2) residual plant protection products in surface waters based on a yearly monitoring program, and (3) the area of land under organic cultivation (Swedish Environmental Objectives Portal, 2009). The goal for land under *certified* organic cultivation in Sweden has been set to 20% by the year 2010. In 2008, the share was well below 10% (6.8% according to the World Resources Institute) (WRI, 2008).

C. Environmental Performance Index to Assess National Agro-Environmental Performance

Beginning in 2000, Yale University’s Center for Environmental Law and Policy, and Columbia University’s Center for International Earth Science Information Network, developed an instrument for benchmarking national environmental performance. Initially this instrument was called the Environmental Sustainability Index but in 2008 was renamed the Environmental Performance Index (CELP/CIESIN, 2008). The overall objective of the Index is to facilitate assessment of current environmental health (stresses on human health) and ecosystem vitality (related to loss or degradation of ecosystems and natural resources). The Environmental Performance Index (EPI) provides an absolute measure of performance by assessing countries on a “proximity-to-target” basis focusing on areas within governmental control and using a number of fixed targets. For the agricultural policy category, there are five proxies used for sustainable agriculture: agricultural subsidies, burnt land area, irrigation stress, pesticide regulation, and proportion of crop land in agricultural landscapes.

Regulation of pesticides. Because of the lack of data on pesticide use and impact data, the Environmental Performance Index measures pesticide regulation, a policy variable that tracks government attention to the issue. The pesticide regulation indicator is based on national participation in the Rotterdam Convention on Prior Informed Consent (http://www.pic.int), which controls trade restriction and regulations for toxic chemicals, and the Stockholm Convention on Persistent Organic Pollutants (http://chm.pops.int), which aims at a global phase-out of a number of persistent organic pollutants (POPs). The pesticide regulation indicator also considers national efforts to ban nine POP pesticides now obsolete in agriculture: aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, and camphechlor (toxaphene).

The two conventions and nine pesticides yield a total of 11 measures, each assigned two points, allowing a target score of 22. Countries, thus, receive the maximum 22 points if they have signed both conventions and submitted a national implementation plan, as well as banned the nine pesticides (CELP/CIESIN, 2008).

In Section E below, the pesticide regulation indicator is used with two other indicators to illustrate agro-environmental performance in 11 major coffee-producing countries and three other countries.

Percentage of crop land area in agriculture-dominated landscapes. The basis for this indicator is the assumption that if more than 30% of the area of a given landscape is under intensive agricultural production, then major ecosystem functions are likely to be compromised. Furthermore, if this level reaches 60%, key ecosystem functions would be difficult to conserve (CELP/CIESIN, 2008).

The crop land intensity indicator measures the proportion of crop land in agricultural landscapes, and sets a target of 40% uncultivated land in areas of crop production. Uncultivated land includes land left fallow, grazing land, and settlements. Hence, this target is set to be conservative. The indicator does not assume that it is better to have mixed mosaics than to have large protected areas. The indicator considers only whether each 10 km × 10 km ‘grid cell’ where cropping occurs has at least 40% uncultivated land, providing space for other ecosystem functions. If agriculture makes up more than 60% of the grid cell, the agricultural land in that grid cell is considered to be intensive. The agricultural intensity thus is calculated as percentage of grid cells with more than 40% cultivated land. Table 3, Section E, shows the performance of selected countries.

D. Environmental Impact Quotients for Comparative Assessment of Pesticides or of Pest Control Strategies

A method to calculate the potential environmental impact of pesticides has been developed by Kovach *et al.* (1992). The work began as a reaction to the fact that the wealth of existing environmental impact data is not readily available or organized in a manner that is usable to the IPM (Integrated Pest Management) practitioner. The method, consequently, was developed to help growers and other IPM practitioners to make more environmentally sound pesticide choices.

The Environmental Impact Quotient (EIQ) comprises three distinctively separate effects: (1) health effects on the farm worker, (2) potential health effects on the [food] consumer, and (3) ecological effects. The 'EIQ Total' is the unweighed average of the three components. Health effects consider both acute and chronic toxicity.

The impact of pesticides on terrestrial systems is determined by summing the toxicities of the chemicals to birds, bees, and beneficial arthropods. Since terrestrial organisms are more likely to occur in commercial agricultural settings than fish, more weight is given to the pesticide's effects on these terrestrial organisms.

$$\text{EIQ}_{Ecology} = (\text{fish toxicity} * \text{surface loss potential}) + (\text{bird toxicity} * ((\text{soil half-life} + \text{plant surface half-life})/2) * 3) + (\text{bee toxicity} * \text{plant surface half-life} * 3) + (\text{beneficial arthropod toxicity} * \text{plant surface half-life} * 5)$$

A critique of the approach has been published by Dushoff *et al.* (1994) arguing that the environmental effects of pesticides are too complex to summarize as a single number.

Table 1 shows eleven insecticides with particularly low EIQ ecology components (Kovach *et al*., 2009). The overall range for insecticides is 12–204. A comparison between the EIQ ecology component and the total EIQ value shows that for all insecticides included in Table 1, the ecology component is higher than the total value. The total EIQ is the mean value of the three components for ecology, farmer and [food] consumer. For all 11 pesticides, therefore, the potential ecological impact is higher than the potential for adverse health hazards to either the farmer or to the consumer or both.

Currently available EIQ values (Kovach *et al*., 2009) indicate that the potential ecological impact for many insecticides is considerably higher than for any herbicide or fungicide. Extreme values (range) for insecticides are 12–204 (for flonicamid and fipronil, respectively), 16–115 for herbicides (azafenidin and naptalam, and fenoxaprop-ethyl, respectively), and 12–148 for fungicides (*Bacillus licheniformis* and copper sulfate, respectively, with organic chemical fungicides in between these values). Copper-based fungicides are of concern as they contaminate the soil, can negatively affect soil organisms, and concentrations have been shown to exceed European legislative limits in many vineyard soils (Paoletti *et al*., 1998; Komárek *et al*., 2010)

The *Prior Informed Consent* (PIC) procedure of the Rotterdam Convention currently covers (a) twenty-three discrete pesticides (active substances), (b) all pesticides (active substances) containing mercury in the molecular structure, and (c) selected formulations of six active substances. These active substances and formulated products have been included in the Convention because they have been banned or severely restricted in a number of countries due to unacceptable effects on human health or the environment. Of the pesticides (mercury compounds excluded) currently under the Rotterdam Convention only 15 are classified according to the World Health Organization's guidelines for classification of pesticides by acute health hazard (WHO, 2004). Nine pesticides are considered by WHO to be

TABLE 1

Environmental Impact Quotients (EIQ) for eleven insecticides with particularly low evidence of ecological impact. Insecticides in alphabetical order

Insecticides	EIQ Ecology component	EIQ Total	Notes
Azadirachtin	25	12	Naturally occurring in neem oil and in seeds of the neem tree *Azadirachta indica.* WHO hazard classification unavailable
Bacillus thuringiensis kurstaki	31	13	Protein crystals and bacterial spores. Unlikely to cause acute health hazard in normal use (WHO)
Cyromazine	33	18	Unlikely to cause acute health hazard in normal use (WHO)
Fenoxycarb	28	14	Unlikely to cause acute health hazard in normal use (WHO)
Flonicamid	12	9	WHO hazard classification unavailable
Fosthiazate	29	14	WHO hazard classification unavailable
Lufenuron	34	16	WHO hazard classification unavailable
Pirimicarb	34	16	Moderately hazardous to health (WHO)
Pymetrozine	28	20	WHO hazard classification unavailable
Triazophos	37	36	Highly hazardous to health (WHO)
Trichlorfon	38	20	Moderately hazardous to health (WHO)

Source: Kovach *et al.* (2009).

TABLE 2
Ecological and human health impact of nine of the pesticides currently covered by the PIC procedure of the Rotterdam Convention and five other pesticides selected for their particularly high values of the EIQ ecology component

Ecological impact → Acute health hazard↓	EIQ ecology component in first or second quartile (low impact) (1)	EIQ ecology component in second or third quartile (high impact)
Highly to extremely hazardous to health	Captafol (PIC) Carbofuran (PIC, SF) DNOC (PIC) Methamidophos (PIC, SF) Parathion-methyl (PIC, SF) Phosphamidon (PIC, SF)	Disulfoton Fenamiphos
Slightly to moderately hazardous to health or unlikely to cause acute hazard in normal use	Benomyl (PIC, SF) Chlordane (PIC) Thiram (PIC, SF)	Copper sulphate Fipronil Propargite

(1) PIC = Prior Informed Consent procedure under the Rotterdam Convention; SF = selected formulations only.

obsolete, three are fumigants. As such they are exempt from hazard classification. With regard to ecological effects, Environmental Impact Quotients are available for only eight of the PIC pesticides. Nine pesticides have a WHO hazard classification as well as an EIQ (‘PIC’ in Table 2). An additional five pesticides not covered under the Convention but with very high values for EIQ are included in Table 2 for comparison. Each of them has an EIQ for ecology in the range 165–204, considerably higher than those for the least disruptive pesticides (range 12–38) shown in Table 1.

E. Monitoring of National Agro-environmental Performance: The Case of Coffee Producing Countries

The capacity of major coffee-producing countries to regulate and control a set of particularly hazardous pesticides is illustrated in Table 3. This table also shows crop land intensity as an indicator of agro-ecological performance. In addition, organic land area as percent of total agricultural area (WRI, 2008) has been included as a third indicator. The capacity to regulate pesticides varies widely among the coffee-producing countries. Some are at about the same level as New

TABLE 3
Selected agro-environmental performance indicators for the eleven major coffee producing countries (1) and three other countries. Countries in alphabetical order by group. Units are explained in Sections C and D of Chapter II

Country	Capacity to regulate pesticides, points (2)	Crop land intensity, percentage of grid cells with more than 40% cultivation (2)	Crop land intensity, proximity to target, percent	Land area under organic cultivation, percent of total agricultural area (3)
Brazil	20	2.0	96.8	0.34
Colombia	19	0.0	99.9	0.07
Ethiopia	5	1.0	98.4	(Data not available)
Guatemala	0	5.9	90.7	0.33
Honduras	1	1.3	97.9	0.06
India	3	51	20.1	0.06
Indonesia	19	11	82.8	0.12
Mexico	18	9.7	84.7	0.27
Peru	21	0.1	99.8	0.85
Uganda	1	32	49.5	0.99
Vietnam	20	12	81.4	0.07
New Zealand	22	1.7	97.4	0.26
Sweden	22	16	75.0	6.8
United States	19	17	73.4	0.22

(1) Countries with 2% or more of world market; Source: International Coffee Organization (http://www.ico.org accessed 8 March 2009).
(2) Source: CELP/CIESIN (2008).
(3) Source: WRI (2008).

Zealand, Sweden, and the United States while others appear to be almost without any regulatory structure. Crop intensity is lower in the coffee-producing countries than in two of the industrialized nations added for comparison, with the exception of India and Uganda. Several coffee-producing countries (Brazil, Guatemala, Peru, and Uganda) seem to have a special interest in organic production as witnessed by an organic land area proportionally larger than that in the United States or New Zealand.

III. IMPACT REDUCTION IN CHEMICAL PEST CONTROL WITH EXAMPLES FROM RICE AND COFFEE CULTIVATIONS

A. Conventional/Chemical Pest Control

Pesticide problems and problem pesticides. Starting with Rachel Carson's book *Silent Spring* in 1962, the world has seen a stream of personal accounts and scientific reports on untoward health and environmental effects of pesticides. Some of these reports have turned out to be global eye-openers. *The Dirty Dozen Campaign* of the Pesticide Action Network in 1985 originally covered 12 particularly hazardous pesticides (Schonfield *et al.*, 1995; PAN, 2009). This campaign with time turned out to be a precursor to the much more recent Rotterdam and Stockholm Conventions, the latter containing a 'dirty dozen' of particularly persistent organic pollutants or POPs (Johansen, 2003). Fifteen of the now 18 'Dirty Dozen' pesticides (aldrin/dieldrin/endrin, camphechlor, chlordane, chlordimeform, DDT, EDB, HCH, heptachlor, lindane, parathion, parathion-methyl, PCP and 2,4,5-T) have been included in one or both of the international conventions. Only aldicarb, DBCP and paraquat, the last one arguably one of the most controversial of the dirty dozen pesticides, remain unregulated through international pesticide conventions.

In 1990, two United Nations agencies provided an unprecedented compilation and assessment of health effects in the *Public Health Impact of Pesticides Used in Agriculture* (WHO/UNEP, 1990). In 1993, the Pesticides Trust (predecessor of PAN UK) published a G*lobal Health and Environmental Audit* (Dinham, 1993) with accounts of pesticide hazards in Brazil, Costa Rica, Ecuador, Egypt, India, Malaysia, Paraguay, South Africa and Venezuela. *The Dependency Syndrome*, yet another aspect of conventional chemical pest control, has been described by the Pesticide Action Network (Williamson, 2003). *The Pesticide Detox*, a recent work on health and environmental impact from pesticides, contains several accounts of a new era aiming at a more sustainable agriculture (Pretty, 2005).

Pesticide sales and consumption. Data on global sales of pesticides in value terms are relatively abundant compared to the publicly available information on production and use in terms of weight of active ingredients. The following references are selected examples of open and commercial, primary and secondary information sources:

- Ag Chem Base, AGRANOVA, Agrochemicals-Executive Review, Ag Chem Base
- Agricultural inputs and the environment—Pesticide use per unit land area, Agriculture for Development, World Development Report 2008, Appendix 3, pp. 324–325; http://go.worldbank.or/2IL9T6CGo0
- AGROW World Crop Protection News and Analysis
- AGROW's Complete Guide to Generic Pesticides, Vol 1–3
- Earth Trends—The Environmental Information Portal, World Resources Institute; http://earthtrends.wri.org/searchable_db/index.php?theme=8
- Environmental Outlook for the Chemicals Industry 2001, Organization for Economic Co-operation and Development; http://www.oecd.org/dataoecd/7/45/2375538.pdf
- FAOSTAT—Database on pesticides consumption. Food and Agriculture Organization of the United Nations; http://faostat.fao.org/site/424/default.aspx#ancor
- FAOSTAT—Database on pesticide trade, Food and Agriculture Organization of the United Nations; http://faostat.fao.org/site/423/default.aspx#ancor
- Market analyses, Pesticides News, Pesticide Action Network UK
- Pesticide Industry Sales and Usage 1994-2001, US Environmental Protection Agency; http://www.epa.gov/opp00001/pestsales/
- UN COMTRADE database; http://comtrade.un.org/db
- UN Industrial Commodity Statistics Yearbook 2006; http://unstats.un.org/unsd/industry/icsy_intro.asp

The annual Production Yearbook (1958-2003) of the Food and Agriculture Organization of the United Nations has, over the years, included data only from a limited number of countries. Published data has been neither uniform in character nor regularly updated. FAO has, more recently, created a web based Database on Pesticide Consumption, which, regrettably, has inherited the basic problems of the Yearbook, viz. lack of regular and reliable input from UN member governments. In a note to the database, FAO declares that:

> "The Statistics Division of the Food and Agriculture Organization of the United Nations started the collection of data on consumption of major individual pesticide products about three decades ago. However, the response to the related Pesticides Consumption Annual Questionnaire sent to all member countries was not very encouraging. Therefore, in 1986 in co-operation with the Commission of the European Union, a study was undertaken to find ways to improve the country coverage of the data. The present work of collecting data on groups of pesticides is a result of the recommendations of this study. Data collected earlier have been published in various issues of the Production Yearbook."

Pesticide markets and pesticide consumption patterns have been analyzed by Pretty and Hine (2005), and Dinham (2005a; 2005b). Dinham recognizes AGROW Reports as an invaluable source of sound analysis of market developments and comprehensive up-to-date material on the agrochemical industry, and acknowledges the fact that she has "drawn heavily" on information in the 2004 and 2005 editions of 'AGROW's Top 20' (Dinham, 2005b).

The total world consumption 1998–1999 (average) was 2.5 million metric tons calculated as active substance, of which 37% herbicides, 25% insecticides, 10% fungicides, and 28% other pesticides (e.g., nematicides, fumigants, rodenticides). In 2002 and 2004, annual shares of global sales values were 27–30% for North America, 25% for Asia/Pacific, 22–24% for "Western Europe" (with the European Union bridging post WW2 "western" and "eastern" Europe, this is an obsolete connotation), 12–14% for Latin America, and 10–11% for the rest of the world. The global agrochemicals market grew 26% in 2008 (7.8% in 2007) to an impressive 41 700 million USD (AGROW website, www.agrow.com).

Largest herbicide use is from the two generic (out-of-patent) herbicides glyphosate (sales value USD 5 000 million) and paraquat (sales value USD 400 million) (Anonymous, 2006). The global use of all pesticides is highly concentrated (85% of the crop protection market) on a few major crops: fruits and vegetables, rice, maize, wheat and barley, cotton, and soy bean.

Six multinational corporations control 75–80% of the world's agrochemical market: Syngenta, Bayer, Monsanto, BASF, Dow, and DuPont. Some 20% of the market is made up of Japanese companies and, increasingly, producers of out-of-patent, or *generic*, products. A number of developing countries are producers and exporters of pesticides. India and China are the largest producers of generic products followed by Argentina. China is the world's largest agrochemical producer by volume (Dinham, 2005a).

B. Rational Pesticide Use

Pesticides will remain a tool for modern agriculture and therefore it is important to design strategies that will reduce pesticide impact. Rational pesticide use (RPU), considered as a 'subset' of Integrated Pest Management (IPM), is a pest control strategy that aims at maximum efficacy with minimum health and environmental impact, and with minimum food residues. This can be achieved by a minimum use of chemical pesticides using the following principles (Dent, 2005):

- Accurate diagnosis of pest problems;
- Forecasting of outbreaks;
- Optimized timing of interventions for *maximum* long-term efficiency and *minimum* pesticide use;
- Selection of a pesticide with *minimum* impact on non-target organisms and the operator;
- Improved application of the selected pesticide for *maximum* dose transfer to the biological target, reduced pesticide costs, *minimum* contamination of the environment and the operator, and *minimum* residues on food crops.

C. 'Safe Use'

CropLife International, a federation representing the plant science industry, promotes the benefits of chemical crop protection and biotechnology products, their importance to sustainable agriculture and food production, 'Safe use,' and the responsible marketing and use of plant protection products through stewardship activities. The purpose of the 'Safe use' initiative is to mitigate problems from use, overuse or misuse of pesticides, particularly in developing countries.

In South Africa, CropLife South Africa promotes the benefits of 'Safe use' as a promising combination with Integrated Pest Management :"Farmers in Africa and the Middle East are increasingly recognizing the substantial benefits that the safe use of crop protection products, combined with Integrated Pest Management (IPM) can bring. The benefits include: Stable and reliable yields; Longer product life cycles; Reduced severity of pest infestations; Decreased pest resistance; Improved crop profitability; and Establishment of higher standards" (CropLife South Africa, 2008).

Obstacles to safe use. Obstacles to safe use vary from country to country and are—in the views of the industry—primarily the result of nonexistent or inadequate education and/or regulation. Typical obstacles include (CropLife International, 2009):

- A comparatively low level of formal education;
- Little or no knowledge of crop protection products and their use;
- Traditionally unsafe practices;
- Improper application of crop protection products, typically by overdosage;
- Unsuitable protective clothing or resistance to wearing protective clothing;
- Inadequate or nonexistent supervision by regulatory authorities;
- Absence of statutory controls on crop protection products.

In a critical review of the 'Safe use' strategy, Murray and Taylor (2001) claim that a multi-sectoral approach is needed to solve pesticide-related problems involving not only the pesticide industry but also the government and civil society. In addition, an alternative approach is recommended based on hazard reduction principles commonly found in industrial safety programs. A phased approach to reduce hazards has been proposed by Sherwood *et al.* (2005): *First*, eliminate the most toxic pesticides; Introduce safer crop protection products or alternative technologies; Implement administrative controls including training and education; Introduce personal protective equipment.

D. Risk Phrases to Indicate Environmental Hazards

Use of a pesticide may have an impact on one or several levels of ecological organization: the individual, population, community or ecosystem level. Most information with regard to ecological effects, however, has been obtained from studies on single species as well as on single pesticides. Classification and labelling of pesticides, consequently, is often based on effects of individual pesticides on populations of single species rather than mixed communities and complex ecosystems. A prescribed list of tests involving a small number of species forms the basis for determining the classification of environmental effects. In the European Union the following risk phrases are currently used for describing environmental hazards (CEC, 2001; HSE, 2008): R 50 Very toxic to aquatic organisms, R 51 Toxic to aquatic organisms, R 52 Harmful to aquatic organisms, R 53 May cause long-term adverse effects in the aquatic environment, R 54 Toxic to flora, R 55 Toxic to fauna, R 56 Toxic to soil organisms, R 57 Toxic to bees, R 58 May cause long-term adverse effects in the environment, R 59 Dangerous for the ozone layer. Appendix 1 shows risk phrases for selected rice pesticides.

E. Environmental Impact of Selected Pesticides Used in Rice Cultivation

The international Codex Alimentarius Commission has recommended maximum residue limits (MRL) for 21 rice pesticides (see Appendix 1) and an extraneous maximum residue limit (EMRL) for chlordane (CAC, 2008). Appendix 1 contains for each pesticide with a Codex MRL information with regard to the ecology component of the Environmental Impact Quotient, environmental risk phrases of the European Union, and environmental hazard information included in the International Chemical Safety Cards (IPCS/INCHEM, 2009).

The EU risk phrases (available for 17 of the 21 pesticides) all deal with aquatic toxicity (Swedish Chemicals Agency, 2009a; 2009b). None of the pesticides in the Appendix has been classified in the EU as toxic to flora (R54), fauna (R55), soil organisms (R56), or bees (R57). International Chemical Safety Cards (available for 13 of the 21 pesticides), however, in five cases there is a statement that *special attention* should be given to non-aquatic organisms when using carbaryl, carbofuran, chlorpyriphos, fenitrothion or fipronil.

F. Impact Reduction in Rice Cultivation through IPM and Farmer Field Schools

In the 1970s and 1980s, the Indonesian government achieved great success in increasing rice yields during the food intensification program . This program was based on adoption of modern agricultural technology, including intensive use of pesticides (Oka, 1991). By the mid 1980s, however, problems had occurred with massive outbreaks of the brown planthopper (BPH, *Nilaparvata lugens*), insecticide resistant populations of the brown planthopper, emerging environmental problems, and cases of death and poisoning. This resulted in political action in the form of a presidential decree (Oka, 1991) that stipulated use of Integrated Pest Management (IPM) for rice pests. Education in IPM was carried out in *Farmer Field Schools*. Farmers and advisers learned that many insects present in the field are enemies of pest insects. The concept of economic thresholds and understanding of harmful effects of inappropriate use of pesticides were important components of the training. Participating farmers were reported to reduce pesticide use by about 56% while boosting yields by roughly 10% (Oka, 1997).

Insecticide use by rice farmers in Indonesia has been shown to be a likely cause of pest problems due to the fact that early season applications killed natural enemies and alternative prey (Settle *et al*., 1996). In addition, in agricultural landscapes dominated by extensive and synchronous cultivation of rice, pest problems were much more severe than in areas with small-scale holdings and more crop diversity. This study was carried out as part of the national IPM program that included Farmer Field Schools. Reduction of pesticide use can be achieved while maintaining yields if farmers develop knowledge about ecological principles. Field Schools have been instrumental in changing farmers' perceptions of a pest threat. Being able to identify insects found in a crop that are beneficial rather than harmful helps moderate insecticide use. Although approximately 1 million farmers had been trained in Farmer Field Schools by 1999 this is only about 5% of the rice farmers in Indonesia (Resosudarmo and Yamazaki, 2007). Knowledge dissemination is very important, but maintenance and reinforcement of this knowledge is essential if farmers are to continue using IPM procedures after graduating from Farmer Field Schools. Approaches other than Farmer Field Schools are also being developed; entertainment as education can reinforce the lessons learned in IPM education and bring them to a wider audience. One example is a radio soap opera developed for a Vietnamese audience (Heong *et al*., 2008). Farmers can change their "pesticide behavior" if empowered through education. It is, however, essential that this change is supported by the community as well as by governmental policies.

G. Impact Reduction in Coffee Cultivations through Continuous Improvement

A *common code for the coffee community* has been elaborated in a collaborative effort to promote and encourage sustainability in the green coffee chain. The Code regulates, on a voluntary basis, the transformation of a variety of cropping practices and conditions, towards economic, environmental and social sustainability in this sector. The desirable transformation, is continuous and described as a three-step ladder (4C Association, 2009).

The starting point in many cases is characterized by the use of the most hazardous pesticides (see Red Criterion pesticides in Table 4). At this level, there is no system in place to minimize spraying. Hence, production systems depending on pesticides of this group are considered to lack the basic characteristics of sustainability. To improve, these pest control practices must be discontinued within a transitional period. The first step leads to an intermediate level with practices improved but still in need of further improvement within a fixed transition period. At this level, a system to minimize spraying such as using economic thresholds and monitoring must be in place and all pesticides

TABLE 4
Number of pesticides used on coffee in Brazil, Costa Rica, El Salvador, Tanzania or Vietnam grouped by sustainability criteria established for the Common Code for the Coffee Community

	Number of insecticides	Number of fungicides	Number of herbicides	Total number of pesticides
Red Criterion pesticides	20	8	5	33
Yellow Criterion pesticides	32	19	9	60
Green Criterion pesticides	5	19	12	36
Total	57	46	26	129

Source: Jansen (2005).

used must be of a lower acute toxicity (Yellow Criterion pesticides in Table 4).

The second step leads to the desirable sustainable practices. Crop management practices; for example utilizing shade, appropriate fertilization, pest-tolerant varieties, and adjusting plant density; for the prevention of phytosanitary problems are in use. Use of natural enemies and the least toxic pesticides is practised. Pesticides used at this level (Green Criterion pesticides in Table 4) include those that might be used within an Integrated Pest Management (IPM) strategy. Because new evidence of harmful side effects might appear, the list has to be revised on a regular basis. A sustainable strategy for controlling pests, diseases and weeds has to be based on management practices able to prevent or reduce these problems. Selective weed management, healthy plant growth through good soil management, shade and ventilation control, cultural practices such as collection of crop residues and protection of natural enemies have to be measures applied first in a pest management strategy. At this level pesticides are only complementary tools for controlling problems (Jansen, 2005).

Table 4 summarizes the result of a survey of coffee pesticides in five major coffee producing countries. Pesticides are grouped by hazard level as defined by the Common Code for the Coffee Community Association. Red criterion pesticides are those with a high acute toxicity (WHO classes Ia and Ib) (WHO, 2004) and/or strong evidence of carcinogenicity or endocrine disruptive effects. Yellow criterion pesticides include moderately hazardous pesticides (WHO class II), pesticides with lower acute toxicity but with other adverse health effects. Green criterion pesticides include the least hazardous pesticides potentially useful within an Integrated Pest Management strategy (Jansen, 2005).

H. Reduced Risk Pesticides for Rice

The United States Environmental Protection Agency allows manufacturers to register conventional chemical pesticides under a ‘Reduced Risk and Organophosphate Alternative’ scheme (EPA, 2008). Advantages of conventional reduced risk pesticides over existing conventional pesticides include:

- Low impact on human health;
- Lower toxicity to non-target organisms;
- Low potential for groundwater contamination;
- Low use rates;
- Low pest resistance potential;
- Compatibility with Integrated Pest Management practices.

Reduced-risk registrations apply to specified uses only. Current risk-reduced conventional pesticides and organophosphorus alternatives for use on rice include the fungicides azoxystrobin and trifloxystrobin, the herbicides cyhalofop-butyl, glufosinate-ammonium, imazethapyr and penoxsulam, and the insecticides gamma-cyhalothrin, zeta-cypermethrin, etofenprox and spinetoram.

I. Impact Reduction Based on Sustainable Green Coffee Principles and Practices

The Sustainable Agriculture Initiative (SAI)—a food industry platform established to support the development of and communication about sustainable agriculture and involving all stakeholders in the food chain—has published principles and practices for sustainable green coffee production (SAI, 2007). SAI has included *continuous improvement* in the definition of a sustainable farming system. Records must be kept on the application of agrochemical inputs providing details of date, product and amount used. To achieve environmental sustainability, biodiversity and natural ecosystems shall be preserved and whenever possible improved in coffee areas and on coffee plantations. Whenever feasible, preference should be given to shade-tree cultivation. Alternatively, significant forest areas established or maintained as *ecological compensation zones.* Shade cover has been shown to be particularly beneficial in coffee agricultural systems and agroforestry may play an important role in reducing system vulnerability (Lin *et al*., 2008). Favourable conditions should be created for natural enemies of frequent pests and diseases of coffee plants. Crop protection should be realised through Integrated Pest Management that puts the emphasis on mechanical and biological means of control. For easy implementation of the principles and practices for sustainable green coffee production, SAI has made a ‘Coffee Toolbox’ available on their website (www.saiplatform.org).

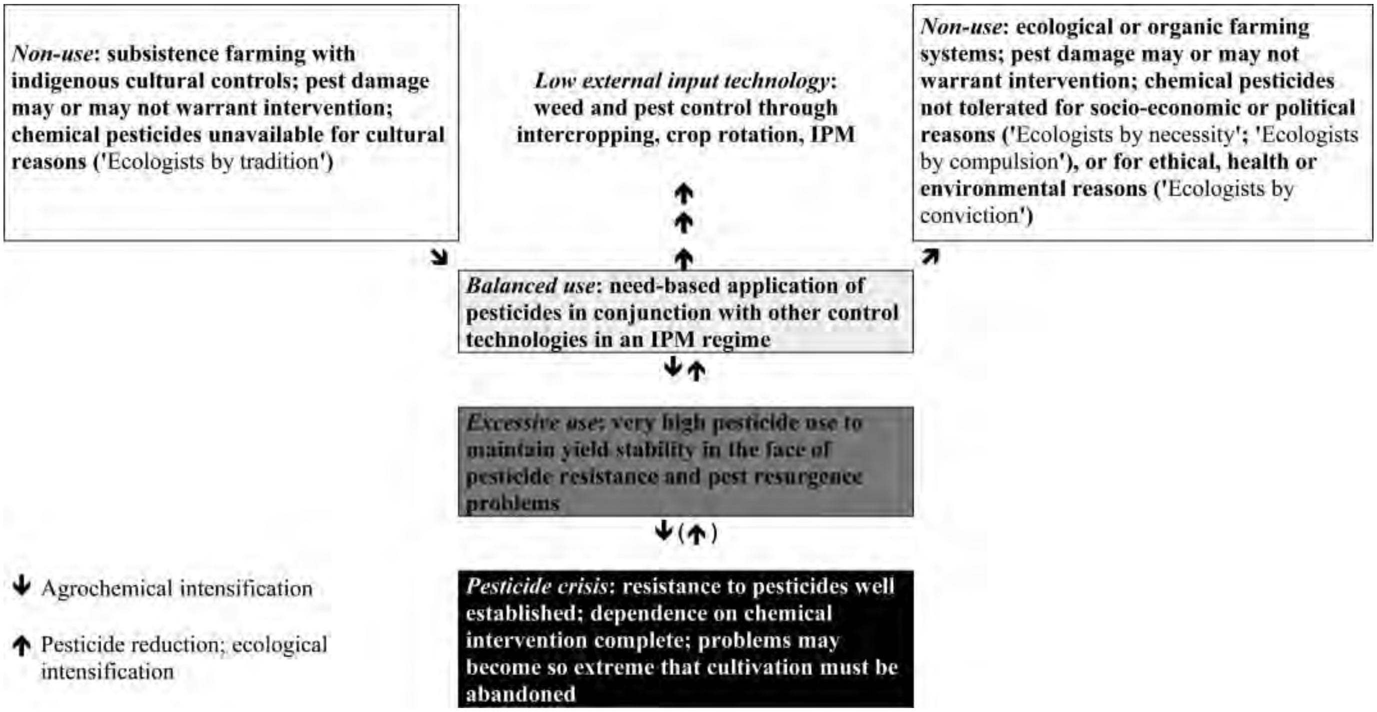

FIG. 1. Agrochemical intensity levels Adapted from A Synopsis of Integrated Pest Management in Developing Countries, Natural Resources Institue (UK), 1992.

IV. LOW EXTERNAL INPUT TECHNOLOGY—ECOLOGICAL APPROACHES TO PEST MANAGEMENT

A. Agrochemical Intensity Levels

The chemical intensity in any farming system may increase from a stage of non-use (see Non-use in Fig. 1) where chemical pesticides may not be available to a situation where problems caused by pesticides may be so severe that cultivation has to be abandoned (Pesticide Crisis in Figure 1). From intensive stages such as excessive use, *pesticide reduction* should be an option; moving from a state of reliance on pesticides and excessive use to a balanced situation where pesticides are used within an Integrated Pest Management regime, or pesticide use is constrained by other governing factors. Pesticide intensity can be decreased further through low external input technology or non-use (by choice or through legislation).

Low external input technologies (LEIT) comprise a variety of mainly biological pest control strategies including those used in Integrated Pest Management (Tripp, 2006) but excluding the rational pesticide use (RPU) as a 'subset' of IPM. The new *Thematic Strategy for Sustainable Use of Pesticides* in the European Union is an example of high-level and large-scale ambitions to guarantee a balanced use of pesticides in agriculture as a minimum standard with options for an even lower external input strategy in agriculture (CEC, 2006). The following are the objectives of the strategy:

- Minimizing the hazards and risks to health and the environment from the use of pesticides;
- Improved controls on the use and transportation of pesticides;
- Reducing the levels of harmful active substances by substituting the most dangerous with safer (including non-chemical) alternatives;
- Encouragement of the use of low-input or pesticide-free cultivation by raising users' awareness, promoting the use of codes of good practice, and consideration of the possible application of financial instruments;
- A transparent system for reporting and monitoring progress made, including the development of suitable indicators.

The Centre for Information on Low External Input and Sustainable Agriculture (ILEIA) promotes the adoption of low external input technology through a website and an international magazine (LEISA) in English supplemented by seven regional editions for Latin America, India, Indonesia, West Africa, East Africa, Brazil, and China, respectively (ILEIA, 2009). LEISA recently has published several timely articles on environment-conscious pest control and climate change (Bijlmakers *et al.*, 2007; Lanting, 2007; Schut and Sherwood, 2007; Shah and Ameta, 2008; Winarto *et al.*, 2008).

The relative importance of current pest control strategies in vegetable crops by geographical region have been summarized

TABLE 5
Relative importance of current pest control strategies in vegetable crops by geographical region

Region	Relative importance of applied pest control strategies
Africa	1. Cultural
	2. Chemical
	3. Mechanical
Europe	1. Biological
	2. Integrated
	3. Chemical
North and Central America	1. Chemical
	2. Integrated
	3. Biological
South America	1. Chemical
	2. Biological
	3. Cultural
Asia	1. Chemical
	2. Biological
	3. Integrated
Australia and the Pacific	1. Chemical
	2. Integrated
	3. Biological

Source: Wright and Hoffmann (2007).

by Wright and Hoffmann (2007), see Table 5. Chemical control is at the top of the list for most of the regions, despite the fact that large research efforts have been put into alternatives to chemical control of many vegetable pests. This continued reliance on chemicals is also at odds with the growing consumer awareness of the problems of pesticide residues in edible products (Ekström and Palmborg, 2006).

B. Good Agricultural Practice and the European Integrated Farming Framework

Good Agricultural Practice (GAP) is defined by the International Code of Conduct on the Distribution and Use of Pesticides (FAO, 2002) as the officially recommended or nationally authorized uses under actual conditions necessary for effective and reliable pest control. It encompasses a range of levels of pesticide applications up to the highest authorized use, applied in a manner which leaves a residue which is the smallest amount practicable. FAO, the United Nations Food and Agriculture Organization, maintains a website for ten farm-level GAP applications (FAO, 2009). The FAO GAP recommendations are all non-prescriptive and voluntary in character. The 'Crop Protection GAP' contains recommendations aiming at Integrated Pest Management, judicious use of pesticides and minimized use of "agrochemicals."

The European Initiative for Sustainable Development in Agriculture (EISA) is an alliance consisting of a small group of national agricultural associations. EISA has agreed on a European Integrated Farming Framework (EISA, 2006) and a Common Codex for Integrated Farming (EISA, 2009). The alliance encourages pest control measures that have minimal impact on the environment and human health and which promote sustainability and profitability. Management of crop health is an essential part of any farming system if yield, quality, profit and food safety are to be maintained. Integrated Farming achieves this by a structured and long-term approach based on the premises that prevention of problems with pests and diseases is better than cure.

Integrated farming encourages continuous improvement in pest control measures. A guiding principle is that a well-established and well-managed crop will be more competitive with weeds, more resilient to attack from pests and diseases and, therefore, should require fewer inputs of crop protection products.

The Integrated Farming Framework gives guidelines which in some parts exceed the codes of Good Agricultural Practice. Crop protection relies principally on cultural, biological, and mechanical control mechanisms as a first resort, together with a considerate use of registered "crop protection products," in other words used with regard to environment and economic considerations.

EISA maintains that the key differences between *integrated farming* and codes of *Good Agricultural Practice* (GAP) are that the former encourages farmers to look at the whole farm with a management and planning approach, which combines the best of traditional practice with the best of modern technology, using regular internal benchmarking for continuous improvement. GAP, in contrast, emphasizes rules and regulations concerning the use, application, and storage of pesticides. Integrated farming stipulates formulation of crop protection management plans, staff training in disease and weed identification, and strategies to avoid build up of resistance. Overall, integrated farming should encompass *continuous monitoring* of whether applicable standards are being maintained or improved, and a *continuous evaluation* of results as well as possible side effects, and hence *permanent improvement* of the farming systems

C. Organic Agriculture. Resilience. Biodiversity

Organic production has increased steadily and is now considered an important part of agricultural production in many countries (Badgley *et al*., 2007). This is partly in response to consumer demands for organically grown products. Another reason is that some countries, particularly in the European Union, have offered incentives for 'going organic'; most often in the form of economic subsidies. Sweden has around 7% of its agricultural land in certified organic production (Swedish Environmental Objectives Portal, 2009). Different farmers have different motivations for changing to organic agriculture. Reasons will range from ideological based convictions to deciding that organic production will be more profitable (Figure 1).

An important concept for a sustainable agro-ecosystem is that of *resilience*. After a disturbance, a robust ecosystem should be able to rebuild and renew itself. Agriculture is replete with disturbance; soil tillage, sowing of the crop, harvesting, and use of pesticides are common in many systems. Intensification of agriculture tends to deplete arthropod species richness (Attwood *et al*., 2008) as loss of diversity in vegetation species and structure will reduce habitat diversity. As the number of species becomes small the ecosystem is more vulnerable because some functional groups may be reduced. For example, if the numbers of one species of predatory insects are greatly reduced there may be other species that can ‘pick up the slack’. But in a system with low biodiversity there could be a lack of species that could fill the void (Tscharntke *et al*., 2005) and the ecosystem service of biological control would decrease. Related to resilience is the capacity of ecosystems to resist invasion. Many pest species invade crops, sometimes migrating large distances, and the action of resident natural enemies can control this invasion (Settle *et al*., 1996; Östman *et al*., 2001). Without these enemies the pests will cause economic damage. Use of insecticides to control a pest species will also reduce the abundance of natural enemies, which are often more sensitive to chemical control, and pest numbers may resurge in the absence of biological control.

Although there are many studies that have found that *biodiversity*, in general, is higher on organic farms than on conventional farms (Letourneau and Bothwell, 2008) only a few have demonstrated that the same trend is true for biological control (Östman *et al*., 2001). This comparison is not necessarily useful for organic growers as they do not use pesticides and must rely on non-chemical methods to reduce pest attack. Organic growers can use substitutions for insecticides such as micro-organisms or botanicals, they can use management practices such as inter cropping, trap cropping, and mulching aimed at increasing natural enemy abundance or repelling pests from the crop, or a combination of the two (Nicholls and Altieri, 2007).

V. SUSTAINABLE PEST MANAGEMENT IN THE FACE OF HUNGER, POVERTY, CLIMATE CHANGE AND POPULATION GROWTH: A CHALLENGE FOR AGRICULTURE AND THE INTERNATIONAL COMMUNITY

A. Current Crop Losses Due to Pests

In 1985, Edwards in a paper on *agrochemicals as pollutants* characterized the crop losses caused by pests as ‘enormous.’ In the article, Edwards (1985) estimated losses of potential crop yields. For a total of 12 crops (vegetables and pulses (grouped together), cocoa, coffee, copra, cotton, maize, potatoes, rice, soya beans, sugar cane, wheat) the estimated crop losses in South America were 28–48 % (average 38%), 30– 5 % (average 45%) in Asia, and 30– 1 % (average 50%) in Africa. Particularly high losses by continent were estimated for maize in Africa (75% potential crop loss), sugar cane in Asia (71% potential loss), and cocoa in South America (48% potential crop loss) (Edwards, 1985).

TABLE 6

Potential and actual crop losses due to animal pests, weeds and pathogens in six major crops worldwide 2001-2003. Crops in order of highest potential loss to lowest (1) Figures in brackets indicate ranges, variation among 19 regions. Averages have been rounded in this table

Crop	Total potential loss (1), per cent	Total actual loss, per cent
Cotton	82 (76–85)	29 (12–48)
Rice	77 (64–80)	37 (22–51)
Potatoes	75 (73–80)	40 (24–59)
Maize	69 (58–75)	31 (18–58)
Soy beans	60 (49–69)	26 (11–49)
Wheat	50 (44–54)	28 (14–40)

Source: Adapted from Oerke (2007).

The conclusions of the United Nations Conference on Environment and Development (UNCED, 1992) stated that world food demand projections indicate an increase of 50% by the year 2000 and demand will more than double again by 2050. Conservative estimates put pre-harvest and post-harvest losses caused by pests between 25 and 50%.

Oerke (2007) estimated potential and actual worldwide crop losses due to pests, weeds and pathogens in six major crops (cotton, maize, potatoes, rice, soybeans, and wheat) 2001-2003. Overall *potential loss* (if no crop protection methods are used, these can be compared to estimates by Edwards (1985) that are reported above) ranged from 44 to 85% and *actual loss* (when using current control practices) ranged from 11 to 59% (Table 6). The magnitude of potential loss is particularly unsettling as this is a measure of crop vulnerability if protection methods should fail. In addition, actual losses are alarmingly high even though pesticides are used, which raises the question of how reliable pesticides are. Negative effects on natural enemies, for example, may actually increase damage by pests.

B. Effects of Climate Change—The Intergovernmental Panel on Climate Change

By the year 2020, in some countries in Africa, yields from rain-fed agriculture could be reduced by up to 50% (IPCC, 2007). Agricultural production, including access to food, in many African countries is projected to be severely compromised. By 2030, production from agriculture is anticipated to decline over much of southern and eastern Australia and over parts of eastern New Zealand, due to increased drought and fires. Production of some important crops in Latin America is predicted to decrease with adverse consequences for food security. In temperate zones, increases in soy bean yields are forecasted.

Overall, an increase in the number of people at risk of hunger is foreseen, in stark contrast to the Millennium Development Goals (IPCC, 2007).

With regard to food security, complex and locally negative impacts on small holders and subsistence farmers are expected. Cereal productivity will tend to decrease in low latitudes and increase at mid to high latitudes. Projections include increased yields in colder environments, decreased yields in warmer environments and increased outbreaks of insect pests. *Appropriate adaptation strategies, however, can reduce vulnerability, both in the short and long term.* Examples given by the IPCC include adjustment of planting dates and crop variety, crop relocation, and improved land management, e.g., soil protection through tree planting.

C. The "Three Worlds of Agriculture"

Three of every four poor people in developing countries live in rural areas, 2.1 billion living on less than 2 USD per day and 800 million on less than 1 USD per day. Most of them depend on agriculture for their livelihoods. The World Development Report 2008 (World Bank, 2008) warns that the agricultural sector must be placed at the centre of the development agenda if the goal of reducing extreme poverty and hunger by half by 2015 is to be realized.

A combination of policies can make agriculture more environmentally sustainable, e.g., investing in technologies. *Many promising technological innovations can make agriculture more sustainable.* Examples include pest control that relies on biodiversity and biological control more than on pesticides. Such technologies are often location-specific, their development and adoption requires more decentralized and participatory approaches, often involving collective action by farmers and communities that are supported by governments.

The World Development Report defines *Three Worlds of Agriculture*: agriculture based, transforming, and urbanized, respectively, each with its own recommended agenda and necessary policy attention. Table 7 summarizes IPPC predictions of effects of climate change, and the World Bank priorities for development in the Three Worlds of Agriculture.

D. Need for Multiple Knowledge—International Assessment of Agricultural Knowledge, Science and Technology for Development

The International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) was designed to function as a policy guide for stakeholders worldwide. Global cereal demands are estimated to increase by 75% between 2000 and 2050, more than three fourths of the growth in demand is projected to be in developing countries. Emphasis on increasing yields and productivity may, however, have negative consequences on environmental sustainability. The IAASTD stresses the need for multiple sources of knowledge, traditional as well as formal. Intensified use of local and formal agricultural knowledge, science and technology is needed to develop and deploy suitable cultivars adaptable to site-specific conditions and which can lead to an increase of small-scale diversification. Opportunities that could improve sustainability and reduce negative environmental effects include resource conservation technologies, improved techniques for *organic and low-input systems*, a wide range of breeding techniques for temperature and pest tolerance, biological control methods for current and emerging pests and plant diseases, and biological substitutes for chemical pesticides (IAASTD, 2008).

In contrast to World Bank priorities, *knowledge* is set at the center of IAASTD priorities. An increase and strengthening of agricultural knowledge, science and technology towards ecological sciences will contribute to addressing environmental issues while at the same time maintaining or increasing productivity. Public policy, regulatory frameworks and international agreements are critical if more sustainable agricultural practices are to be implemented (IAASTD, 2008).

VI. PROMOTING ADAPTIVE PEST MANAGEMENT IN THE GLOBAL SOUTH

A. Thirty Years and No Change?

Thirty years ago, the International Commission on International Development Issues reflected on the need of new farming systems in developing countries appropriate for local circumstances, job creation, and ecological balance:

> It is important to appreciate that new models are needed for agricultural development in the Third World. The western agricultural model with its high degree of mechanization and use of chemicals cannot be simply transferred to developing countries. There are many examples of mechanization increasing output and employment, and chemical fertilizers and pesticides have contributed importantly to raising yields, especially with new plant varieties. But there have also been examples of unthinking transfers of inappropriate techniques, mechanization leading to significant job destruction at the local level and ill-advised application of agricultural chemicals. The need to develop farming systems appropriate to local circumstances, attentive in particular to employment creation in rural areas which may help stem the drift to the cities, and to ecological balance, is part of the case for increasing local research capacity. (Brandt, 1979)

Concerns raised over pesticides in developing countries thirty years ago are as much a reality today as then. Hazardous pesticides are still used with little or no personal protection. Application equipment is inadequately maintained, faulty or not even available. Most users have no access to washing facilities or, in the event of accidents, medical services. Illiteracy is still high in many rural areas while good reading skills are needed to interpret complex label instructions—even if they are written in the local language.

Governments in developing countries need to invest more in the skills required to interpret scientific and technical data and use it to make sound local risk assessments and to implement regulations. Resources for raising awareness are equally crucial.

TABLE 7
The Three Worlds of Agriculture, predicted effects of climate change, and World Bank priorities for agricultural development

Agriculture-based countries of Sub-Saharan Africa	Transforming countries of Asia, the Middle East and North Africa (1)	Urbanized countries in Latin America and the Caribbean (2)
Predicted effects of climate change (3)		
By 2020, in some countries, yields from rain-fed agriculture could be reduced by up to 50%. Agricultural production, including access to food, in many African countries is projected to be severely compromised. This would further adversely affect food security and exacerbate malnutrition.	Increased yields in colder environments, decreased yields in warmer environments, and increased insect outbreaks is the generally applicable prognosis.	Productivity of some important crops is projected to decrease with adverse consequences for food security. In temperate zones, soy bean yields are projected to increase. Overall, the number of people at risk of hunger is projected to increase.
World Bank priorities for agricultural development (4)		
(a) Building markets and value chains; (b) A smallholder-based productivity revolution in agriculture; (c) Expanding agricultural exports; (d) Securing the livelihood and food security of subsistence farmers; (e) Labour mobility and rural nonfarm development ("beyond agriculture")	(a) From green revolution to the new agriculture; (b) Dealing with water scarcity; (c) Making intensive systems more sustainable; (d) Development of lagging areas; (e) Rural development off the farm, linked to towns; (f) Skills for successful migration; (g) Safety nets for those left behind	(a) Improving livelihoods in subsistence agriculture and providing social assistance; (b) Supplying environmental services; (c) Territorial development to create rural jobs

(1) Two countries in this region (India and China) are the world's largest producers of generic pesticides. India is also the world's largest producer of organophosphorus pesticides. China is the world's second largest agrochemical producer by volume (450 thousand tons in 2000).
(2) A country in this region (Argentina) is the world's third largest producer of generic pesticides.
(3) Sources: Anonymous (2008), based on IPCC (2007).
(4) Source: World Bank (2008).

Most users of pesticides in developing countries not only have a limited perception of the risks, but also a high acceptance of risk due to competing priorities essential for survival (Dinham and Ekström, 2000).

B. Particular Needs of Small-scale Farmers in Africa

Whereas agriculture has had a decisive significance for growth in many Asian countries, shortcomings in African agriculture may have led to a stagnated development in many African countries (Gerremo, 2008). Why then has there not been more attention devoted to these issues over the years? African agricultural sectors demonstrate, through continuous low growth rates and deepening rural poverty, the impact of externally imposed agricultural policies. African farmers have faced deteriorating production and market conditions and struggled largely unaided for the last 25 years. Smallholder farmers are often in competition with large-scale farmers who receive preferential state support despite strong evidence that smallholder farmers are more equitable and more efficient per unit of land. In addition, with the rolling back of the state, extension services have virtually collapsed (Havnevik *et al*., 2007).

One suggested solution may be a comprehensive African sustainable agricultural revolution based on new solutions with a smallholder focus and with wide stakeholder collaboration. The *Alliance for a Green Revolution in Africa* (AGRA) is an African-led partnership working across the African continent to help millions of small-scale farmers and their families lift themselves out of poverty and hunger. AGRA programs are designed to develop practical solutions to significantly boost farm productivity and incomes for the poor while safeguarding the environment. AGRA advocates policies that support its work across all key aspects of African agriculture from seeds, soil health and water to markets and agricultural education (website www.agra-alliance.org). A skeptical view on an African Green Revolution has been mirrored by Rieff (2008).

Another possible solution is *organic agriculture*, increasingly promoted by various actors. In 2008 UNCTAD, the United Nations Conference on Trade and Development, and UNEP, the United Nations Environment Programme, jointly noted that Africa is home to 20–24 percent of the world's certified organic farms. Organic agriculture, however, is virtually absent in agricultural education, extension and research and development in Africa (UNEP/UNCTAD, 2008). The following are recommendations on best practices for organic policy that are aimed at developing country government (UNEP/UNCTAD, 2009):

- Setting sustainable agriculture as a priority;
- Assessing current policies and programs, and remove disincentives to sustainable/ecological/organic agriculture—for example, subsidies on agrochemicals;
- Training extension workers in sustainable agricultural practices and varieties;
- Encouraging farmer-to-farmer exchanges;
- Compiling and disseminating indigenous agricultural knowledge and varieties;
- Funding research on sustainable agriculture, building on indigenous knowledge, and in partnership with farmers;
- Promoting development of local and regional markets for organic products;

The Millennium Villages. A practical plan on how to achieve the United Nations Millennium Goals in Africa has been designed by Sachs and co-workers (2005). A total of twelve clusters of *Millennium Villages* in Sub-Saharan Africa were selected to represent agro-ecological zones in Africa: maize (mixed crop), highland (mixed crop), highland perennial, pastoral, agro-silvo-pastoral, cereal–root crops (mixed), root crops, tree crops, coastal artisanal fishing, and irrigated systems.

Each of the 12 clusters of villages is located in a distinct agro-ecological zone, arid or humid, highland or lowland, grain producing or pastoral. These agro-ecological zones represent 93% of the agricultural land area in Sub-Saharan Africa, and the homes of 90% of the agricultural population. The plan was designed to demonstrate how tailored strategies can overcome the range of farming, water, plant disease, and infrastructure challenges facing the continent.

C. Field Schools for Weather Vigilance and Adaptation to Climate Change

Farmer Field Schools (FFS) were designed by the United Nations Food and Agriculture Organization to promote Integrated Pest Management in Southeast Asia in a step away from overuse of chemical pesticides in rice cultivation. The Farmer Field School approach has since then been applied in other parts of the world, e.g., Sub-Saharan Africa, and used to study IPM in vegetables and some other crops. FFS programs have so far been initiated in 78 countries with four million graduates. Six countries (Bangladesh, China, India, Indonesia, the Philippines and Vietnam) account for 91% of the graduates. Crop health, not pest control, has been the central theme in most FFS curricula. FFS projects in Africa have placed more emphasis on crop production and marketing and less on crop protection (van den Berg and Jiggins, 2007). In Latin America and the Caribbean farmer-to-farmer training and participatory research is being conducted by the *Campesino a Campesino* (farmer-to-farmer) *Movement*. Sustainable agriculture and livelihoods through integration of new ecological practices with older, more traditional methods is in progress in Mexico, Central America and Cuba (Holt-Gimenez, 2006).

Characteristic components of a Farmer Field School comprise field investigations in study plots and surrounding fields, learning by doing through hands-on work, weekly meetings ideally over a full growing season or natural crop cycle, field observations of insect pests, weeds, diseases, and natural enemies, agro-ecosystem analysis in small groups, presentations, discussions and documentation through writing and drawings. The groups may consist of 25–30 peer farmers (men and women) assisted by a facilitator. The facilitator, ideally, is a person familiar with the setting and the issues to be demonstrated and discussed. He or she may have an affiliation in the national government (e.g. Extension), a civil society organization, or the private sector (Gallagher, 1999; 2003).

The Farmer Field School approach started with an Integrated Pest Management focus but has undergone a transition into other areas such as organic agriculture, and has expanded into generally assisting communities, *Community IPM*. Consequently, in addition to the primary goal of training farmers to be experts in their own fields, FFS graduates may also become trainers conducting FFS for others in their community, engage in local research activities to optimise practices for the local situation, engage in training curriculum development activities with trainers and researchers, take the lead in local planning, implementation and evaluation of IPM activities at community level, including fund raising from local government, the farmer community or other organizations in their area (Mörner *et al*., 2002).

In response to emerging threats from increasingly unpredictable weather conditions, extreme weather events and gradual climate change ('global warming') (IPCC, 2007), experimental *Climate Field Schools* have been set up in Indonesia. In these field schools, farmers should document plant development so that they can detect differences in crop phenology and growth in relation to climatic trends. This documentation should include abundance of pests and incidence of diseases in the crop as well as the plant protection measured used. In some societies there will be traditional information on changes in cropping systems over long periods of time. Gathering of this type of information is combined with education on the causes and consequences of climate change. In addition, weather forecasts can be disseminated to farmers and the possible effect of the coming weather on the crop can be discussed at field school sessions. Winarto *et al*. (2008) in a recent study concluded that climate change is an additional reason to build resilience in farmers' livelihoods.

VII. CONCLUSIONS

Pest Management for the Future. The United Nations Conference on Environment and Development in 1992 concluded that chemical control of agricultural pests dominated the scene and that *Integrated Pest Management*—combining biological control, host plant resistance and appropriate farming practices, and minimizing the use of pesticides—was the best option for the future. Consequently, Integrated Pest Management should go hand in hand with appropriate pesticide management to allow for pesticide regulation and control, including trade, and for the safe handling and disposal of pesticides, especially those that are particularly toxic and persistent (UNCED, 1992). These conclusions in our view are still valid.

In line with these conclusions, the International Code of Conduct on the Distribution and Use of Pesticides sets voluntary standards designed to promote Integrated Pest Management. The United Nations Food and Agriculture Organization has developed pest management guidelines to support the implementation of the Code. Integrated Pest Management is a central element of the Code.

The EU strategy for sustainable pesticide use requires that member states establish all necessary conditions for the implementation of Integrated Pest Management by professional pesticide users. IPM principles will be mandatory for farmers in the EU as of 2014. This is a bold goal and it should result in reduction of pesticide use. It remains to be seen if the IPM programs that will be developed will be widely implemented for the variety of crops in the European setting.

Rational Pesticide Use as Part of an IPM Regime. Use of chemical pesticides will continue to be a component of modern agriculture for some time to come. *Rational pesticide use* aims at maximum efficacy using a minimum of pesticides with optimised timing of interventions for maximum long-term efficiency and the lowest possible pesticide use. Selection of pesticides with a low impact on non-target organisms and the general environment will continue to be important. By using classifications and appropriate labelling that provide important information on the environmental—and health—hazards of pesticides, the environmental risks can be taken into consideration when choosing plant protection products. Improvements in application techniques ('precision farming') should be explored so that there will be maximum dose transfer to the biological target, minimum contamination of the environment, low exposure to the user, and minimum residues on food crops. Because new evidence of harmful side effects might appear, the classification of pesticides has to be revised—and communicated—on a regular basis.

Pesticide Reduction through Continuous Improvement. Pesticide reduction has been used by governments and other actors as a systematic and targeted method to reduce reliance on pesticides, food residues, use and overall health and environmental risks of chemical pesticides. A number of quantitative methods have been developed to monitor and evaluate progress and to enable appropriate feedback to concerned stakeholders and the general public. The principle of *continuous improvement* of pest management methods has been incorporated into a 'Common Code for the Coffee Community' and should be universally applicable.

All stakeholders should strive for continuous improvement in pest management. Initially this involves a discontinuation of the most hazardous pesticides and, with time, *substitution* of remaining hazardous pesticides with less hazardous ones. At the starting point there may be no system in place to minimize pesticide use and the production systems may lack the basic characteristics of sustainability. The first step therefore may lead to an intermediate level with improved management, with a need of further improvement within a fixed transition period. At this level, all pesticides used should be of low toxicity to human health and the environment. A system to minimize pesticide use, such as Integrated Pest Management, should also be in place. Further actions lead to an increase in non-chemical crop management practices including use of natural enemies, diversification of the agro-ecosystem, use of cultural controls such as crop rotation, enhancement of biodiversity, and use of the least toxic pesticides only as a last resort. Pesticides used at this level should include only those compatible with an Integrated Pest Management strategy.

Building Resilience and Promoting Adaptive Pest Management. Intensification of agriculture has contributed to the loss of ecosystem services and reduced the resilience of the system. This is due, in part, to the use of chemical pesticides that lessen biodiversity and pollute the environment. Consequently, there is a need to monitor and assess both the environmental and economic impacts of plant protection measures involving pesticides. In order to restore ecosystem services and build resilience and sustainability, rational pest control practices must be based on ecological knowledge. This is, by no means, a simple task as plant protection schemes will have to be developed or revised in order to, increasingly, take local conditions into consideration.

Farmers and policy makers will have to be educated about the ecological interactions in agriculture. They must also learn to deal with changing conditions and be able to analyze new situations. These educational programs may take the form of Farmer Field Schools, Climate Field Schools, or public education schemes through the media. *Different cultures and geographical regions will necessarily have to adapt educational components to fit with local circumstances*. The ultimate goal is to build *resilience* into farmers' livelihoods and food production. To do so, information is needed on a variety of issues and on several learning levels. Regional, national, and global research facilities must play important roles in such a process. It is, however, not enough to fund research. Stakeholders must be an integral part of the process and governments must give substantial and sustained support; in the forms of financial support, policy development, and legislation in order to succeed in environmentally sound pest management.

REFERENCES

Anonymous. 2006. Growing sales of generic pesticides – Profiting from the past. *Pesticides News* **71:** 8–9. http://www.pan-uk.org/pestnews/Issue/pn71/pn71p8.pdf. Accessed on 5 July 2010.

Anonymous. 2008. Observed changes in climate: Their effects, causes, and projected climate change and impact. *Currents* **44/45:** 6–11. Swedish University of Agricultural Sciences, Uppsala

Attwood, S. J., Maron, M., House, A.P.N., and Zammit, C. 2008. Do arthropod assemblages display globally consistent responses to intensified agricultural land use and management? *Global Ecology and Biogeography* **17:** 585–599.

Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, M. J., Avilés-Vázques, K., Samulon, A., and Perfecto, I. 2007. Organic agriculture and the global food supply. *Renewable Agriculture and Food Systems* **22:** 86–108.

Bergkvist, P. 2004. *Pesticide Risk Indicators at National and Farm Levels—A Swedish Approach.* Swedish Chemicals Agency, http://www.kemi.se/Upload/Trycksaker/Pdf/PM/PM6_04.pdf. Accessed on 15 April 2009.

Bijlmakers, H., and Ashraful Islam, M. 2007. Changing the strategies of farmer field schools in Bangladesh. *LEISA Magazine* **23**(4): 21–23.

Brandt, W. 1979. *North-South: A Programme for Survival.* Independent Commission on International Development Issues.

4C Association. 2009. *The 4C Code of Conduct: Unacceptable Practices and 4C Code Matrix.* http://www.4c-coffeeassociation.org/en/code-of-conduct.php Accessed on 18 January 2010.

CAC (Codex Alimentarius Commission). 2008. *Maximum Residue Limits.* Codex Alimentarius Commission, http://www.codexalimentarius.net/mrls/pestdes/jsp/pest_q-e.jsp Accessed on 10 January 2009.

Carson, R. 1962. *Silent Spring*. Houghton Mifflin, Boston.

CEC (Commission of the European Communities). 2001. Commission Directive 2001/59/EC relating to the classification, packaging and labelling of dangerous preparations, Commission of the European Communities.

CEC (Commission of the European Communities). 2006. *Thematic Strategy for Sustainable Use of Pesticides* [website], Commission of the European Communities, http://ec.europa.eu/environment/ppps/home.htm . Accessed on 29 October 2008.

CELP/CIESIN. 2008. *Environmental Performance Index 2008.* Center for Environmental Law and Policy, Yale University, and Center for International Earth Science Information Network, Columbia University, http://www.yale.edu/epi/files/2008EPI_Text.pdf Accessed on 3 November 2008.

CropLife International. 2009. *Safe Use at a Glance.* http://www.croplife.org//website/pages/SafeUse_Glance.aspx . Accessed on 26 January 2009.

CropLife South Africa. 2008. *Reaping the Benefits of IPM*, http://www.croplife.org/website/pages/SafeUse_Africa.aspx Accessed on 29 October 2008.

Dent, D. 2005. Overview of agrobiologicals and alternatives to synthetic pesticides. **In:** *The Pesticide Detox: Towards a More Sustainable Agriculture.* pp. 70–82. Pretty, J., Ed., Earthscan, London, Sterling, VA.

Dinham, B. 1993. *The Pesticide Hazard – A Global Health and Environmental Audit.* The Pesticides Trust, UK.

Dinham, B. 2005a. Corporations and pesticides. **In:** *The Pesticide Detox: Towards a More Sustainable Agriculture.* pp. 55–69. Pretty, J., Ed., Earthscan, London, Sterling, VA.

Dinham B. 2005b. Agrochemical markets soar – Pest pressures or corporate design? *Pesticides News* **68:** 9–11.

Dinham, B., and Ekström, G. 2000. Donors urged to help combat pesticide hazards, *Pesticides News* 49, 12-13, http://www.pan-uk.org/pestnews/Issue/pn49/pn49p12.htm . Accessed on 30 January 2009.

Dushoff, J., Caldwell, B., and Mohler, C. L. 1994. Evaluating the environmental effect of pesticides: A critique of the environmental impact quotient. *American Entomologist* **Fall:** 180–184.

Dyer, L.A., and Letourneau D. 2003. Top-down and bottom up diversity cascades in detritus and living food webs. *Ecol. Lett.* **6:** 60–68.

Edwards, C. E. 1985. Agrochemicals as environmental pollutants. **In:** *Control of Pesticide Applications and Residues in Food: A Guide and Directory.* pp. 1–19. von Hofsten, B. and Ekström, G., Eds., Swedish Science Press, Uppsala.

EISA (European Initiative for Sustainable Development in Agriculture). 2006. *European Integrated Farming Framework.* A European Definition and Characterisation of Integrated Farming as Guideline for Sustainable Development of Agriculture, European Initiative for Sustainable Development in Agriculture, http://www.sustainable-agriculture.org/stuff/EISA-Framework-english-28-September-2006.pdf . Accessed on 29 September 2008.

EISA (European Initiative for Sustainable Development in Agriculture). 2009. *A Common Codex for Integrated Farming.* European Initiative for Sustainable Development in Agriculture, http://www.sustainable-agriculture.org/codex.pdf. Accessed on 16 February 2009.

Ekbom, B. 2000. Interchanges of insects between agricultural and surrounding landscapes. **In:** *Interchanges of Insects Between Agricultural and Surrounding Landscapes.* pp. 1–3. Ekbom, B., Irwin, M., and Robert, Y., Eds., Kluwer Academic Publishers, Dordrecht.

Ekström, G., and Bergkvist, P. 2008. Swedish pesticide reduction 1986-2006. **In:** *Encyclopedia of Pest Management.* DOI: 10.1081/E-EPM-120044723, Pimentel, D., Ed., Taylor & Francis, London.

Ekström, G., and Palmborg, M. 2006. Consumer concerns about pesticides and pests. **In:** *Encyclopedia of Pest Management.* DOI: 10.1081/E-EPM-120009932, Pimentel, D., Ed., Taylor & Francis, London.

EPA (U.S. Environmental Protection Agency). 2008. *Reduced Risk and Organophosphate Alternative Decisions for Conventional Pesticides.* http://www.epa.gov/opprd001/workplan/completionsportrait.pdf Accessed on 24 January 2009.

FAO. 2002. *International Code of Conduct on the Distribution and Use of Pesticides.* Food and Agriculture Organization of the United Nations, (Revised version).

FAO. 2009. *GAP Principles.* Food and Agriculture Organization of the United Nations, http://www.fao.org/prods/GAP/home/principles_en.htm. Accessed on 15 April 2009.

Gallagher, K. 1999. *Farmer Field Schools: A Group Extension Process Based on Adult Non-Formal Education Methods*, http://www.farmerfieldschool.net/document_en/FFS_GUIDe.doc Accessed on 6 March 2009.

Gallagher, K. 2003. Fundamental elements of a farmer field school. *LEISA Magazine*, March: 5-6, http://www.farmerfieldschool.net/document_en/05_06.pdf . Accessed on 4 March 2009.

Gerremo, I. 2008. *Why Has it Taken 25 years?* The World Bank's Reports on Agriculture 1982 and 2008, The Royal Swedish Academy of Agriculture and Forestry, http://www.ksla.se/sv/retrieve_file.asp?n=1561 Accessed on 16 January 2009.

Havnevik, K., Bryceson, D., Birgegård, L.-E., Matondi, P., and Beyene, A. 2007. *African Agriculture and the World Bank: Development or Impoverishment?* Nordic Africa Institute, http://www.nai.uu.se/publications/download.html/978-91-7106-608-4.pdf?id=25256 Accessed on 10 December 2008.

Heong, K. L., Escalada, M. M., Huan, N. H., Ky Ba, V. H., Ouynh, P. V., Thiet, L. V., and Chien, H. V. 2008. Entertainment education and rice pest management: A radio soap opera in Vietnam. *Crop Protection* **27:** 1392–1397.

Holt-Giménez, E. 2006. *Campesino a Campesino: Voices from Latin America's Farmer to Farmer Movement for Sustainable Agriculture*. Food First Books, Oakland.

HSE. 2008. *Symbols, Abbreviations, Risk and Safety Phrases.* Health and Safety Executive (UK), http://www.hse.gov.uk/chip/phrases.htm Accessed on 29 October 2008.

IAASTD. 2008. *Executive Summary of the Synthesis Report and Global Summary for Decision Makers.* International Assessment of Agricultural Knowledge, Science and Technology for Development, http://www.agassessment.org Accessed on 16 March 2009.

ILEIA. 2009. *LEISA Network.* Centre for Information on Low External Input and Sustainable Agriculture, http://www.ileia.org . Accessed on 26 January 2009.

IPCC. 2007. *Climate Change 2007.* Synthesis Report, An Assessment of the Intergovernmental Panel on Climate Change, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf Accessed on 16 Match 2009.

IPCS/INCHEM. 2009. *International Chemical Safety Cards*, Chemical Safety Information from Intergovernmental Organizations, http://www.inchem.org/pages/icsc.html . Accessed on 8 March 2009.

Jansen, A.-E. 2005. *Plant Protection in Coffee – Recommendations for the Common code for the Coffee Community Initiative.* German Agency for Technical Cooperation (GTZ), July 2005.

Johansen, B. E. 2003. *The Dirty Dozen: Toxic Chemicals and the Earth's Future*. Praeger, Westport, CT.

Komárek, M., Čadková, E., Chrastný, V., Bordas, F., and Bollinger, J-C. 2010. Contamination of vineyard soils with fungicides: A review of environmental and toxicological aspects. *Environment International* **36:** 138–151.

Kovach, J., Petzoldt, C., Degni, J., and Tette, J. 1992. A Method to Measure the Environmental Impact of Pesticides. *New York's Food and Life Sciences Bulletin* **139:** 1–8.

Kovach, J., Petzoldt, C., Degni, J., and Tette, J. 2009. *A Method to Measure the Environmental Impact of Pesticides.* New York State Integrated Pest Management Program, Online Publications, http://www.nysipm.cornell.edu/publications/eiq/default.asp Accessed on 10 November 2009.

Landis, D. A., Wratten, S. D., and Gurr, G. A. 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology* **45:** 175–201.

Lanting, M. 2007. Pest Management: The Art of Mimicking Nature. *LEISA Magazine* **23**(4): 6–7.

Letourneau, D. K., and Bothwell, S. G. 2008. Comparison of Organic and Conventional Farms: Challenging Ecologists to Make Biodiversity Functional. *Frontiers in Ecology and the Environment* **6**(8): 430–438.

Lin, B. B., Perfecto, I., and Vandermeer, J. 2008. Synergies between agricultural intensification and climate change could create surprising vulnerability for crops. *BioSciences* **58**(9): 847–854.

Mörner, J., Bos, R., and Fredrix, M. 2002. *Reducing and Eliminating the Use of Persistent Organic Pesticides*, Guidance on Alternative Strategies for Sustainable Pest and Vector Management, United Nations Environment Programme, http://portalserver.unepchemicals.ch/Publications/POPred_E.pdf Accessed on 6 March 2009.

Murray, D. L., and Taylor, P. L. 2001. Beyond safe use: Challenging the international pesticide industry's hazard reduction strategy. International Institute for Environment and Development, *Gatekeeper Series* No 103.

Nicholls, C.I., and Altieri, M.A. 2007. Agroecology: Contributions towards a renewed ecological foundation for pest management. **In:** *Perspectives in Ecological Theory and Integrated Pest Management*. pp. 431v468. Kogan M. and Jepson P., Eds., Cambridge University Press, Cambridge.

Oerke, E. C. 2007. Crop losses to animal pests, plant pathogens, and weeds. **In:** *Encyclopedia of Pest Management*, Volume II. Pp. 116–120. Pimentel, D., Ed., CRC Press, Boca Raton, FL.

Oka, I. N. 1991. Success and challenges of the Indonesia National Integrated Pest Management Program in the rice-based cropping system. *Crop Protection* **10:** 163–165.

Oka, I. N. 1997. Integrated Crop Pest Management with Farmer Participation in Indonesia. **In:** *Reasons for Hope: Instructive Experiences in Rural Development.* pp. 97–109. A. Krishna, N. Uphoff, and M.J. Esman., Eds., Kumarian Press, West Hartford, CT, USA.

Östman, Ö., Ekbom, B., and Bengtsson, J. 2001. Farming practice and landscape heterogeneity influence biological control. *Basic and Applied Ecology* **2:** 365–371.

PAN. 2009. *The List of Lists.* A catalogue of lists of pesticides identifying those associated with particularly harmful or environmental impacts, 3rd Edition. Pesticide Action Network (PAN UK), http://www.pan-uk.org/List%20of%20Lists.html. Accessed on 15 April 2009.

Paoletti, M. G., Sommaggio, D., Favretto, M. R., Petruzzelli, G., Pezzarossa, B., and Barbafieri, M. 1998. Earthworms as useful bioindicators of agroecosystem sustainability in orchards and vineyards with different inputs. *Applied Soil Ecol.* **10:** 137–150.

Pretty, J. (Ed.). 2005. *The Pesticide Detox: Towards a More Sustainable Agriculture.* Earthscan, London, Sterling, VA.

Pretty, J., and Hine, R. 2005. Pesticide Use and the Environment. **In:** *The Pesticide Detox: Towards a More Sustainable Agriculture.* pp. 1–22. Pretty, J., Ed., Earthscan, London, Sterling, VA.

Rieff, D. 2008. A green revolution for Afirca? *New York Times*, October 10, 2008. http://www.nytimes.com/2008/10/12/magazine/12wwlin-shan-t.html. (accessed 21 February 2011)

Resosudarmo, B. P., and Yamazaki, S. 2007. Mass Guidance (BIMAS) vs Farmer Field School: The Indonesian Experience. Paper given at an International Seminar; Sustaining Growth? Economic Transition and Natural Resource Management in East and Southeast Asia; Ho Chi Minh City, 21-22 June 2007. http://www.asia-link-recreate.com/chapter_82.pdf. Accessed 13 July 2009.

Richter, E. D., and Chlamtac, N. 2002. Ames, pesticides, and cancer revisited. *Int. J. Occupational and Environ. Health* **8:** 63–72.

Sachs, J. D. 2005. *Investing in Development,* A Practical Plan to Achieve the Millennium Development Goals, Report to the UN Secretary-General, Millennium Project, http://www.unmillenniumproject.org/mv/mv_closer.htm. Accessed on 15 March 2009.

SAI. 2007. Sustainable green coffee principles and practices – working document. Sustainable Agriculture Initiative, http://saiplatform.org/our-activities/coffee/default.ht . Accessed on 24 January 2009-

Schonfield, A., Anderson, W., and Moore, M. 1995. PAN's dirty dozen campaign – The view at ten years. *Global Pesticide Campaigner* 5(3).

Schut, M., and Sherwood, S. 2007. Farmer field schools in translation: Scaling up in name but not in meaning, *LEISA Magazine* **23:** 28–29.

Settle, W. H., Ariawan, H., Astuti, E. T., Cahyana, W., Hakim, A. L., Hindayana, D., Lestari, A. S., and Pajarningsih, S.1996. Managing tropical rice pests through conservation of natural enemies and alternative prey. *Ecology* **77:** 1975–1988.

Shah, R., and Ameta, N. 2008. Adapting to change with a blend of traditional and improved practices. *LEISA Magazine* **24**(4): 9–11.

Shennan, C. 2008. Biotic interactions, ecological knowledge and agriculture. *Philosophical Transactions of the Royal Society B* 363: 717–739.

Shennan, C., Pisani Gareau, T., and Sirrine, J. R. 2005. Agroecological approaches to pest management in the US. **In:** *The Pesticide Detox: Towards a More Sustainable Agriculture.* pp. 193–211. Pretty, J., Ed., Earthscan, London, Sterling, VA.

Sherwood, S., Cole, D., Crissman, C., and Peredes, M., 2005. From pesticides to people: Improving ecosystem health in the Northern Andes. **In:** *The Pesticide Detox: Towards a More Sustainable Agriculture.* pp. 147–164. Pretty, J., Ed., Earthscan, London, Sterling, VA.

Stern, V. M., Smith, R. F., and van den Bosch, R., and Hagen, K. 1959. The integrated control concept. *Hilgardia* **29:** 81–101.

Swedish Chemicals Agency. 2009a. *The N-Class Database on Environmental Hazard Classification.* http://apps.kemi.se/nclass/ Accessed on 21 September 2009.

Swedish Chemicals Agency. 2009b. *The Classification List.* (in Swedish), http://apps.kemi.se/amnesregistret/ Accessed on 21 September 2009.

Swedish Environmental Objectives Portal, 2009. *A Non-Toxic Environment.* http://www.miljomal.nu/english/obj4.php Accessed on 11 March 2009.

Tripp, R. 2006. Is low external input technology contributing to sustainable agricultural development? *Natural Resource Perspectives* 102, Overseas Development Institute (UK).

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., and Thies, C. 2005. Landscape perspectives on agricultural intensification and biodiversity—ecosystem service management. *Ecol. Letters* **8:** 857–874.

UNCED.1992. *Promoting Sustainable Agriculture and Rural Development.* Agenda 21, Chapter 14, United Nations Conference on Environment and Development.

UNDP. 2008. *Millennium Development Goals.* http://www.undp.org/mdg Accessed on 29 September 2008.

UNEP. 2004. *Childhood Pesticide Poisoning, Information for Advocacy and Action.* http://www.who.int/ceh/publications/pestpoisoning.pdf. Accessed on 13 July 2009.

UNEP/UNCTAD. 2008. Organic agriculture and food security in Africa, http://www.unctad.org/en/docs/ditcted200715_en.pdf. Accessed on 18 August 2009.

UNEP/UNCTAD. 2009. Sustaining African Agriculture-Organic Production. Policy Briefs No. 6, February 2009. http://www.unctad.org/en/docs/presspb20086_en.pdf. (Accessed 20 February 2011)

United Nations. 2008. *Millennium Goals.* http://www.un.org/milleniumgoals Accessed on 29 October 2008.

van den Berg, H. and Jiggins, J. 2007. Investing in farmers – the impact of farmer field schools in relation to integrated pest management. *World Development* **35:** 663-686.

WHO. 2004. *The WHO Recommended Classification of Pesticides by Hazard, and Guidelines to Classification.* http://www.who.int/ipcs/publications/pesticides_hazard/en/ Accessed on 11 March 2009.

WHO/UNEP. 1990. *Public Health Impact of Pesticides Used in Agriculture.* World Health Organization and the United Nations Environment Programme.

Williamson, S. 2003. *The Dependency Syndrome: Pesticide Use by African Smallholders.* Pesticide Action Network (UK).

Winarto, Y. T., Stigter, K., Anantasari, E., and Nur Hidayah, S. 2008. Climate field schools in Indonesia: Improving “response farming” to climate change. *LEISA Magazine* **24(4):** 16—8.

World Bank. 2008. *Agriculture for Development*, World Development Report 2008, http://go.worldbank.org/ZJIAOSUFU0 Accessed on 11 January 2009.

WRI. 2008. *Earth Trends.* The Environmental Information Portal, World Resources Institute, http://earthtrends.wri.org/searchable_db/index.php?theme=8 Accessed on 3 November 2008.

Wright, M. G., and Hoffmann, M. 2007. Vegetable crop pest management: Insects and mites, **In:** *Encyclopedia of Pest Management*, Volume II. pp. 686–688. Pimentel, D., Ed., CRC Press, Boca Raton, FL.

APPENDIX 1

Environmental hazards of selected rice pesticides (1) as reflected by Environmental Impact Quotients, European Union risk phrases, and International Chemical Safety Cards, respectively. Pesticides in alphabetical order. N/A = not available

Pesticides. International Chemical Safety Card No in square brackets (2)	Environmental Impact Quotient : Ecology component (3)	European Union classification of environmental hazard (4)	Environmental hazard information included in International Chemical Safety Cards
2,4-D [33]	31	R52-53	The substance is harmful to aquatic organisms.
Bentazone [828]	31	R52-53	N/A
Carbaryl [121]	75	R50	The substance is very toxic to aquatic organisms. This substance may be hazardous in the environment; *special attention should be given to birds and honey bees.*
Carbendazim [1277]	96	R50-53	The substance is very toxic to aquatic organisms.
Carbofuran [122]	81	R50-53	The substance is very toxic to aquatic organisms. This substance may be hazardous to the environment; *special attention should be given to soil organisms, honey bees and bird*s.
Carbosulfan [N/A]	127	R50-53	N/A
Chlorpyrifos [851]	73	R50-53	The substance is very toxic to aquatic organisms. This substance may be hazardous in the environment; *special attention should be given to birds and honey bees.* Bioaccumulation of this chemical may occur along the food chain, for example in *fish and algae.*
Chlorpyrifos-methyl [N/A]	N/A	R50-53	N/A
Diflubenzuron [N/A]	65	N/A	N/A
Diquat [1363, diquat dibromide]	75	R50-53	The substance is harmful to aquatic organisms.

(Continued on next page)

APPENDIX 1
Environmental hazards of selected rice pesticides (1) as reflected by Environmental Impact Quotients, European Union risk phrases, and International Chemical Safety Cards, respectively. Pesticides in alphabetical order. N/A = not available *(Continued)*

Pesticides. International Chemical Safety Card No in square brackets (2)	Environmental Impact Quotient : Ecology component (3)	European Union classification of environmental hazard (4)	Environmental hazard information included in International Chemical Safety Cards
Fenithrothion [622]	N/A	R50-53	The substance is very toxic to aquatic organisms. This substance may be hazardous to the environment; *special attention should be given to Crustacea and honey bees*. In the food chain important to humans, bioaccumulation takes place, specifically in fish.
Fenthion [655]	N/A	R50-53	The substance is very toxic to aquatic organisms.
Fipronil [1503]	204	R50-53	The substance is very toxic to aquatic organisms. This substance may be hazardous in the environment; *special attention should be given to birds and honey bees*.
Flutolanil [1265]	46	N/A	The substance is toxic to aquatic organisms.
Iprodion [N/A]	48	R50-53	N/A
Methoprene [N/A]	N/A	N/A	N/A
Paraquat [5, paraquat dichloride]	36	R50-53	The substance is very toxic to aquatic organisms. The substance may cause long-term effects in the aquatic environment.
Sulfuryl fluoride [1402]	N/A	R50	N/A
Tebufenozide [N/A]	43	R51-53	N/A
Thiacloprid [N/A]	65	N/A	N/A
Trifloxystrobin [N/A]	56	R50-53	N/A

(1) Pesticides with a Codex Alimentarius Maximum Residue Limit (MRL) in rice; Source: CAC, 2008

(2) Source: IPCS/INCHEM, 2009

(3) A higher EIQ value means a higher ecological impact: Source: Kovach et al., 2009

(4) R50 Very toxic to aquatic organisms; R50-53 Very toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment; R51-53 Toxic to aquatic organisms. May cause long-term adverse effects in the aquatic environment; R52-53 Harmful to aquatic organisms. May cause long-term adverse effects in the aquatic environment. Source: Swedish Chemicals Agency, 2009a and 2009b

Critical Reviews in Plant Sciences, 30:95–124, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554355

Environmental Impact of Different Agricultural Management Practices: Conventional vs. Organic Agriculture

Tiziano Gomiero,[1] David Pimentel,[2] and Maurizio G. Paoletti[1]
[1]*Laboratory of Agroecology and Ethnobiology, Department of Biology, Padova University, Padova, 35121 Italy*
[2]*College of Agriculture and Life Sciences, Cornell University, Ithaca, New York 14853, USA*

Table of Contents

Address correspondence to Tiziano Gomiero, Laboratory of Agroecology and Ethnobiology, Department of Biology, Padova University, Padova, 35121 Italy. E-mail: tiziano.gomiero@libero.it

Referee: Dr. Nadia El-Hage Scialabba, Natural Resources Management and Environment Department FAO, Rome.

Organic agriculture refers to a farming system that enhance soil fertility through maximizing the efficient use of local resources, while foregoing the use of agrochemicals, the use of Genetic Modified Organisms (GMO), as well as that of many synthetic compounds used as food additives. Organic agriculture relies on a number of farming practices based on ecological cycles, and aims at minimizing the environmental impact of the food industry, preserving the long term sustainability of soil and reducing to a minimum the use of non renewable resources. This paper carries out a comparative review of the environmental performances of organic agriculture versus conventional farming, and also discusses the difficulties inherent in this comparison process. The paper first provides an historical background on organic agriculture and briefly reports on some key socioeconomic issues concerning organic farming. It then focuses on how agricultural practices affect soil characteristics: under organic management soil loss is greatly reduced and soil organic matter (SOM) content increases. Soil biochemical and ecological characteristics appear also improved. Furthermore, organically managed soils have a much higher water holding capacity than conventionally managed soils, resulting in much larger yields compared to conventional farming, under conditions of water scarcity. Because of its higher ability to store carbon in the soil, organic agriculture could represent a means to improve CO_2 abatement if adopted on a large scale. Next, the impact on biodiversity is highlighted: organic farming systems generally harbor a larger floral and faunal biodiversity than conventional systems, although when properly managed also the latter can improve biodiversity. Importantly, the landscape surrounding farmed land also appears to have the potential to enhance biodiversity in agricultural areas. The paper then outlines energy use in different agricultural settings: organic agriculture has higher energy efficiency (input/output) but, on average, exhibits lower yields and hence reduced productivity. Nevertheless, overall, organic agriculture appears to perform better than conventional farming, and provides also other important environmental advantages, such as halting the use of harmful chemicals and their spread in the environment and along the trophic chain, and reducing water use. Looking at the future of organic farming, based on the findings presented in this review, there is clearly a need for more research and investment directed to exploring potential of organic farming for reducing the environmental impact of agricultural practices; however, the implications of reduced productivity for the socioeconomic system should also be considered and suitable agricultural policies should be developed.

Keywords organic agriculture, conventional agriculture, sustainability, energy use, GHGs emissions, soil organic matter, carbon sink, biodiversity

I. ORGANIC AGRICULTURE: AN INTRODUCTION

Organic agriculture refers to a farming system that bans the use of agrochemicals such as synthetic fertilizers and pesticides and the use of Genetically Modified Organisms (GMO), as well as many synthetic compounds used as food additives (e.g., preservatives, coloring) (IFOAM, 2008; 2010). Organic agriculture is regulated by international and national institutional bodies, which certify organic products from production to handling and processing (Codex Alimentarius, 2004; Courville, 2006; EC, 2007; USDA, 2007; IFOAM, 2008; 2010). Its origins can be traced back to the 1920–1930 period in North Europe (mostly Germany and UK) (Conford, 2001; Lotter, 2003; Lockeretz, 2007), and it is now widely spread all over the world.

In this paper we will briefly present the history of organic agriculture and introduce the key characteristics of organic practices and principles. The focus of the paper is, then, to review the main literature on the comparison between organic and conventional agriculture concerning their environmental performances. Some socioeconomic issues will also be addressed.

We are aware that conventional agriculture can adopt low input, environmentally friendly approaches to management (as in systems with reduced or no tillage, or integrated pest management farming). However, the very fact that organic agriculture is strictly regulated allows better comparison of the performances of farming systems with and without agrochemical inputs, and with or without the adoption of certain management practices. The main difficulty in comparisons is the blur definition of conventional practices, which range from traditional polycultures to highly industrial monocultures.

We wish to point out that in the review of the literature we found a number of studies published in gray literature (reports, conference proceedings, etc.) in local/national languages, which are then difficult to both reach and read. In this review we choose to reduce to a minimum the references to gray literature because of the difficulty for the reader to find and check the original works.

A. Organic Principles

The International Federation of Organic Agriculture Movements IFOAM, a grassroots international organization born in 1972, that today includes 750 member organizations belonging to 108 countries, for details see http://www.ifoam.org/index.html), states that: “Organic agriculture is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved.” (IFOAM, 2010).

The USDA National Organic Standards Board (NOSB) defines organic agriculture as follows: “Organic agriculture is an ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity. It is based on minimal use of off-farm inputs and on management practices that restore, maintain and enhance ecological harmony." (Gold, 2007).

Organic agriculture relies on a number of farming practices that take full advantage of ecological cycles. In organic farming systems soil fertility is enhanced by crop rotation, intercropping, polyculture, covering crops and mulching. Pest control is achieved by using appropriate cropping techniques, biological control, and natural pesticides (mainly extracted from plants). Weed control, in many cases the main focal problem for organic farming, is managed by appropriate rotation, seeding timing, mechanic cultivation, mulching, transplanting, flaming, etc. (Howard, 1943; Altieri, 1987; Lampkin, 2002; Lotter, 2003; Altieri and Nichols, 2004; Koepf, 2006; Kristiansen *et al*., 2006; Gliessman, 2007). As with any manipulation of a natural ecosystem, biological control must adopt a cautionary approach when introducing novel organisms to fight pests. Cases have been reported where introduced ally insects turned out to cause more harm than those they were supposed to fight (Simberloff and Stiling, 1996; Hamilton, 2000).

According to IFOAM, organic agriculture should be guided by four principles:

- *health*: organic agriculture should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible,
- *ecology*: organic agriculture should be based on living ecological systems and cycles, increased soil organic matter, work with them, emulate them and help sustain them,
- *fairness*: organic agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities,
- *care*: organic agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment.

IFOAM argues that organic agriculture is a holistic production management system which promotes and enhances agroecosystem health, including biodiversity, biological cycles, and soil biological activity. An organic production system is, then, designed to:

- enhance biological diversity within the whole system,
- increase soil biological activity,
- maintain long-term soil fertility,
- recycle plant and animal waste in order to return nutrients to the land, thus minimizing the use of nonrenewable resources,
- rely on renewable resources in locally organized agricultural systems,
- promote the healthy use of soil, water and air as well as minimize all forms of pollution that may result from agricultural practices,
- handle agricultural products with emphasis on careful processing methods in order to maintain the organic integrity and vital qualities of the product at all stages,
- become established on any existing farm through a period of conversion, the appropriate length of which is determined by site-specific factors such as the history of the land, and type of crops and livestock to be produced.

The organic philosophy aims at preserving the natural environment; concern towards local floras and fauna as goals for organic farming are often little understood by consumers and policy makers.

As stated by FAO (2004, p. iii): "Evidence suggests that organic agriculture and sustainable forest management not only produce commodities but build self-generating food systems and connectedness between protected areas. The widespread expansion of these approaches, along with their integration in landscape planning, would be a cost efficient policy option for biodiversity."

Concerning environmental performances, some authors warn that organic practices may not be applicable without considering the specific situation. Wu and Sardo (2010) list a number of examples in which the effects of agricultural techniques employed in organic agriculture could result in worse environmental impacts than conventional practices. The authors, for instance, argue that, on sloping land, environmental damages from erosion due to mechanical weed control can be more harmful than that from chemical origin, e.g., spraying with glyphosate [results from Teasdale *et al*. (2007), for organic farming on 15% slope, indicate that if properly managed and in proper condition, organic farming can still provide benefits for soil]. In addition, Wu and Sardo (2010) suggest that mulching with polyethylene sheets (permitted in organic farming) is more polluting than spraying glyphosate, and that flame weeders (permitted in organic farming) are more costly and energy demanding than glyphosate and much less efficient in the control of perennial weeds. It is to be noted that the evaluation of one practice ought to be contextualized, with the consideration of a range of factors that determine good or bad management of a landscape as a whole. For example, mechanical slope weeding on its own may be detrimental while if considered within the farm architecture, its local impact may be compensated with features such as hedges and perennials that ensure overall soil resilience.

Some authors (e.g., Guthman, 2004) argue that as organic farmers enter large distribution system they may be forced to shift once again into monoculture and industrial agriculture. That is because of the pressure from agrifood corporations that buy and distribute their organic products, and from the market itself.

B. Origins and Present Situation

In order to help the reader to better understand the foundation of organic farming, it may be useful to provide a brief sketch of the history of the organic agriculture movement. For details on this topic we will refer the reader to the extensive works of Conford (2001) and Lockeretz (2007) or, for a more concise summary, to Lotter (2003), Kristiansen (2006), Heckman (2006), and Gold and Gates (2007). Historical information can also be found at the website of the main organic associations such as the British "Soil Association" (http://www.soilassociation.org), or the international IFOAM (http://www.ifoam.org).

The first organized movement by alternative farmers, who wanted to adhere to the traditional way of production refusing the new chemical inputs, appeared in Germany at the end of 1920s. Some tens of farmers, agronomists, doctors and lay people grouped together after attending the lectures of the Austrian philosopher and scientist Rudolf Steiner (who developed also Anthroposophy), in 1924. The experimental circle of anthroposophical farmers immediately tested Steiner's indications in daily farming practice. Three years later a cooperative was formed to market biodynamic products forming the association Demeter (for details see Demeter web page at http://www.demeter.net). In 1928 the first standards for Demeter quality control were formulated. Biodynamic agriculture, as this method is named, is well grounded in the practical aspects of manuring the soil, which is the cornerstone of organic farming, but it also concerns lunar and astrological scheduling, communication with "nature spirits" and the use of special potencies or preparations, that are derived by what might be described as alchemical means (Koepf, 1976; 2006; Conford, 2001). These latter practices are not easily "measurable" in scientific terms, but performance can be assessed using usual agronomic indicators.

While Rudolf Steiner was establishing the roots for the growth of the biodynamic movement, Sir Albert Howard (1873–1947), a British agronomist based in India, was trying to develop a coherent and scientifically based system for preserving soil and crop health. Upon his return to the UK, he worked to promote his new approach (Howard, 1943; Conford, 2001). He was convinced that most agricultural problems were due to soil mismanagement, and that reliance on chemical fertilization could not solve problems such as loss of soil fertility and pest management. He maintained that the new agrochemical approach was misguided, and that it was a product of reductionism by "laboratory hermits" who paid no attention to how nature worked. In his milestone book, *An Agricultural Testament* (1943), Howard described a concept that was to become central to organic farming: "*the Law of Return*" (a concept expressed also by Steiner). The Law of Return states the importance of recycling all organic waste materials, including sewage sludge, back to farmland to maintain soil fertility and the land humus content (Howard 1943; Conford, 2001).

The first use of the word *organic* has been ascribed to Walter Northbourne, the author of *Look to the Land*, an influential book published in 1940 in the UK. Within it, he elaborates on the notion of a farm as an "organic whole," where farming has to be performed as a biologically complete process (Conford, 2001). The term "organic" then, in its original sense, describes a holistic approach to farming: fostering diversity, maintaining optimal plant and animal health, and recycling nutrients through complementary biological interactions.

In 1943 in the UK, Lady Eve Balfour (1899–1990) published the book *The Living Soil*, in which she described the direct connection between farming practice and plant, animal, human and environmental health. The book exerted a significant influence on public opinion, leading in 1946 to the foundation in the UK of "The Soil Association" by a group of farmers, scientists and nutritionists. In the following years, the organisation also developed organic standards and its own certification body. Eve Balfour, who was one of IFOAM's founders, claimed that: "The criteria for a sustainable agriculture can be summed up in one word—permanence, which means adopting techniques that maintain soil fertility indefinitely, that utilise, as far as possible, only renewable resources; to avoid those that grossly pollute the environment; and that foster biological activity throughout the cycles of all the involved food chains" (Balfur, 1977).

In 1940, in an article published in *Fact Digest*, Jerome I. Rodale introduced the term "organic agriculture" in the United States and techniques such as crop rotation and mulching, that have, since then, become accepted organic practices in the United States. Although, the idea of organic agriculture came mostly from the work of Albert Howard. However, Rodale expanded Howard's ideas in his book *Pay Dirt* (Rodale, 1945), adding a number of other "good farming practices."

Since 1990, with increased public concern for the environment and food quality, the organic farming movement has gained the attention of consumers and has undergone national and international institutional regulation (Willer and Yussefi, 2006). According to the recent data by IFAOM (Willer, 2011) there are 37.2 million hectares of organic agricultural land (including in-conversion areas). The regions with the largest areas of organic agricultural land are Oceania (12.2 million hectares—32.8%), Europe (9.3 million hectares—25%), and Latin America (8.6 million hectares—23.1%). The countries with the most organic agricultural land are Australia, Argentina, and the United States. It should be noted that it is difficult to compare figures coming from different countries: most of the area in Australia is pastoral land used for low intensity grazing, therefore one organic hectare in Australia is not directly equivalent (e.g., does not have the same productivity) to one organic hectare in a European country.

In the United States, in 2005, for the first time all 50 states had some certified organic farmland. In 2005, U.S. producers dedicated over 1.6 million ha of farmland to organic production systems: 690,000 ha of cropland and 910,000 ha of rangeland and pasture. California remains the leading State in certified organic cropland, with over 89,000 ha, mostly for fruit and vegetable production (Gold, 2007).

According to the data collected from Willer and Yussefi (2006), the main land uses in organic farming worldwide, as a percentage of the total global organic area, are as follows:

- 5% permanent crops: land cultivated with crops that do not need to be replanted after each harvest, such as cocoa, coffee; this category includes flowering shrubs, fruit trees, nut trees and vines, but excludes trees grown for wood or timber,
- 13% arable land: land used for temporary crops, temporary meadows for mowing or pasture, market and kitchen gardens and land temporarily fallow (less than five years).
- 30% permanent pasture: land used permanently (five years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land),
- 52% certified land the use of which is not known but where wild products are harvested.

C. Organic Standards

Organic farming aims at providing farmers with an income while at the same time protecting soil fertility (e.g., by crops rotation, intercropping, polyculture, cover crops, mulching) and preserving biodiversity (even if tending the local flora and fauna as a goal for organic farming is often little understood by consumers and policy makers), the environment and human health. Broader ethical considerations regarding the above aims have also been made (Halberg *et al*., 2006; IFOAM, 2008).

In Europe, the first regulation on organic farming was drawn up in 1991 (Regulation EEC N° 2092/91 – EEC, 1991). Organic standards prohibit the use of synthetic pesticides and artificial fertilizers, the use of growth hormones and antibiotics in livestock production (a minimum usage of antibiotics is admitted in very specific cases and is strictly regulated). Genetically modified organisms (GMOs) and products derived from GMOs are explicitly excluded from organic production methods.

A revised EU regulation which came into force in 2007 (EC, 2007) added two main new criteria: firstly, food will only be able to carry an organic logo (certified as organic) if at least 95% of the ingredients are organic (nonorganic products will be entitled to indicate organic ingredients on the ingredients list only); secondly, although the use of GMOs will remain prohibited, a limit of 0.9 percent will be allowed as accidental presence of authorised GMOs.

In the United States, Congress passed the Organic Foods Production Act (OFPA) in 1990. The OFPA required the U.S. Department of Agriculture (USDA) to develop national standards for organically produced agricultural products, to assure consumers that agricultural products marketed as organic meet consistent, uniform standards. The OFPA and the National Organic Program (NOP) regulations require that agricultural products labelled as organic originate from farms or handling operations certified by a state or private entity that has been accredited by USDA (Gold, 2007).

Internationally, organic agriculture has been officially recognised by the Codex Alimentarius Commission (CAC).[1] In 1991, the CAC began elaborating guidelines for the production, processing, labelling and marketing of organically produced food, with the participation of observer organizations such as IFOAM and the EU. The CAC approved organic plant production in June 1999, followed by organic animal production in July 2001. The requirements in these CAC Guidelines are in line with IFOAM Basic Standards and the EU Regulation for Organic Food (EU Regulations 2092/91 and1804/99). There are, however, some differences with regard to the details and the areas, which are covered by the different standards.

In the Guidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods, CAC at point 5 states that: “Organic Agriculture is one among the broad spectrum of methodologies which are supportive of the environment. Organic production systems are based on specific and precise standards of production which aim at achieving optimal agroecosystems which are socially, ecologically and economically sustainable.” (Codex Alimentarius, 2004, p. 4).

Some authors (e.g., Vogl *et al*., 2005; Courville, 2006) express concerns about the excessive bureaucratic control posed by standards on farmers, and warns that excessive bureaucratization of organic agriculture can result a serious burden to organic farmers because of the economic effort that it takes to accomplish with all the requirements.

II. SOME ISSUES CONCERNING COMPARATIVE ANALYSIS

Often, different approaches to farming system analysis are employed by different scholars, making comparison of findings difficult: this is especially true with regards to how the boundaries of the farming system are defined. For instance, in accounting for the energy in animal feed or agrochemicals, should we consider the energy spent for transportation? In a time of fast globalization where commodities travel from continent to continent such a question is not a negligible one.

Moreover, farming system may have different geographical, climatic and soil characteristics, different crops, different rotation systems (both in crop species and timing) and different sort of inputs.

Comparative studies tend to focus on specific crops, over a short period of time. Simplifying the focus of the farming system analysis, through single commodity versus whole farm productivity analysis, entails the risk of compromising the understanding of its complex reality and supplying incomplete

---

[1] The Codex Alimentarius Commission was created in 1963 by FAO and WHO to develop food standards, guidelines and related texts such as codes of practice under the Joint FAO/WHO Food Standards Program. The main purposes of this Program is protecting consumer health, ensuring fair trade practices in the food trade, and promoting coordination of all food standards work undertaken by international governmental and non-governmental organizations. (Codex Alimentarius web page at http://www.codexalimentarius.net/web/index_en.jsp)

information. Longer-term studies (e.g. a minimum of 10 years) should be encouraged to gather information—through comparable models—about the true sustainability of different farming systems.

Energy analysis in agriculture is a complex task (Fluck and Baird, 1980; Giampietro *et al*., 1992; Pimentel and Pimentel, 2008; Wood *et al*., 2006; Smil, 2008). Usually energy analysis focuses on fertilizers, pesticides, irrigation and machinery but fails to include important components such as insurance, financial services, repairs and maintenance, veterinary and other services (Fluck and Baird, 1980). Energy efficiency assessment presents many tricky issues (Giampietro *et al*., 1992; Giampierto, 2004; Smil, 2008), and the choice of the system boundary can account for differences as large as 50% on energy estimates among studies (Suh *et al*., 2004; Wood *et al*., 2006), and even higher when coming to the assessment of the whole agri-food system (Giampietro, 2004). Comparing organic and conventional systems is even more difficult (Dalgaard *et al.*, 2001; Haas *et al*., 2001; Pimentel *et al.*, 2005; Küstermann *et al.*, 2008; Thomassen *et al*., 2008; Wu and Sardo, 2010).

Wood *et al*. (2006), for instance, when studying a cohort of organic farmers in Australia, found that when direct energy use, energy related emissions, and greenhouse gas emissions are measured they are higher for the organic farming sample than for a comparable conventional farm sample. But when the whole Life-Cycle Assessment was considered, including the indirect contributions of all above-mentioned secondary factors, then conventional farming practices had a higher energy cost. The authors argue that indirect effects must be taken into account when considering the environmental consequences of farming, in particular with regards to energy use and greenhouse gas emissions. In a comprehensive Life-Cycle Assessment of milk production in The Netherlands, Thomassen *et al.* (2008) compared energy consumption (MJ kg^{-1} of milk) for conventional and organic milk (see also Table 5a and Table 5b). They found that when comparing direct energy consumption conventional performed much better (0.6 MJ kg^{-1} of milk) then organic (0.96 MJ kg^{-1} of milk). But when indirect costs were taken into account, the result was the opposite (conventional 4.47 MJ kg^{-1} of milk and organic 2.17 MJ kg^{-1} of milk). See also Küstermann *et al*. (2008) in section VB for another example concerning GHGs emissions.

Comparing efficiency may not be that simple also within the same experiment. For instance, Gelfand *et al.* (2010) report that an alfalfa growing organic system was half as efficient compared to a conventional system when employing tillage, and had one third of a conventional system efficiency when there was no tillage. But the fact that the authors accounted all the grain (included corn, and soybean) as used directly for human consumption, while alfalfa were not (of course) can be questioned. And, in fact, as the authors correctly argue (Gelfand *et al.,* 2010, p. 4009-4010): "This is because under the Food scenario alfalfa biomass can be used only as ruminant livestock feed and conversion efficiency of forage energy to weight gain by livestock is 9:1. Were we to assume that corn, soybean, and wheat were to be used for livestock production rather than direct human consumption, similar energy conversion efficiencies by livestock would apply. This would result in about 87% lower energy output from the grain systems, similar to Alfalfa energy yields."

This is an important consideration to keep in mind because in an organic farming system the value of a crop has to be understood within a whole cropping system that can span several years. On the contrary, conventional farming can be based on a simple system that alternates corn and soybean on a yearly basis.

To carry on extensive long-term trials for a number of crops in several different geographical areas would be of fundamental importance to understand the potential of organic farming as well as to improve farming techniques in general (Mäder *et al.*, 2002; Pimentel *et al*., 2005; Gomiero *et al*., 2008; Francis *et al*., this issue).

When comparing organic vs. conventional system "farm-to-fork" we should also be aware that a possible disadvantage of organic products is the fact that they account for less than 2% of global food retail: this smaller economic scale compared to conventional systems could contribute to lower energy efficiency of collection, preparation and distribution (El-Hage Scialabba and Müller-Lindenlauf, 2010).

III. SOIL BIOPHYSICAL AND ECOLOGICAL CHARACTERISTICS

In this section we will review the effects of organic agriculture on soil biophysical and ecological characteristics and how these effects relate to the long-term soil fertility. Attempts to develop a soil quality index can provide an effective framework for evaluating the overall effects of different production practices (organic, integrated, conventional etc.) on soil quality (Glover *et al.*, 2000; Mäder *et al*., 2002a; Marinari *et al.*, 2006; Fließbach *et al*., 2007).

A. Soil Erosion and Soil Organic Matter

Soil erosion and loss of Soil Organic Matter (SOM) with the conversion of natural ecosystems to permanent agriculture are the most important and intensively studied and documented consequences of agriculture (Hillel, 1991; Pimentel *et al*., 1995; Lal, 2004, 2010; Montgomery, 2007a; 2007b; Quinton *et al.*, 2010). Intensive farming exacerbates these phenomena, which are threatening the future sustainability of crop production on a global scale, especially under extreme climatic events such as droughts (Reganold *et al*., 1987; Pimentel *et al*., 1995; Mäder *et al.*, 2002a; Sullivan, 2002; Lotter *et al*., 2003; Montgomery, 2007a; 2007b; Lal, 2010; NRC, 2010).

Clark *et al*. (1998) underlined that increases in SOM following the transition to organic management occur slowly, generally taking several years to detect. This is a very important point to be kept in mind when assessing the performances of farming systems under different management practices. Farmers, scientists and policy makers alike should take into consideration the evolving and complex nature of organic farming systems, a complex nature that contrasts with the extreme simplification and large dependency on external input that characterize conventional farming systems. When aiming at long-term sustainability, trade offs should also be considered between obtaining short-term high yields with the aid of agrochemicals, and maintaining soil health.

Given the crucial importance of soil health, the aim of organic agriculture is to augment ecological processes that foster plant nutrition yet conserve soil and water resources. Even if the soil characteristics are generally site-specific, to date many studies have proven organic farming to perform better in preserving or improving soil quality with regards to both biophysical (e.g., SOM) and biological (e.g., biodiversity) properties (e.g., Reganold *et al*., 1987; Reganold, 1995; Clark *et al*., 1998; Drinkwater *et al.*,1998; Siegrist *et al*., 1998; Fließbach *et al*., 2000; 2007; Glover *et al*., 2000; Stölze *et al*., 2000; Stockdale *et al*., 2001; Mäder *et al*., 2002a; Lotter *et al*., 2003; Delate and Cambardella, 2004; Pimentel *et al*., 2005; Kasperczyk and Knickel, 2006; Marriott and Wander, 2006; Briar e*t al*., 2007; Liu *et al*., 2007).

Although few in number, important long-term studies concerning SOM content and soil characteristics in organic and conventional soils have been carried out, both in the United States and Europe. In a long trial of nearly 40 years, Reganold *et al*. (1987) compared soils from organic and conventional farms in Washington, USA. They found that organic fields had surface horizon 3 cm thicker and topsoil 16 cm deeper than conventionally managed fields. Higher SOM matter content (along with other better biochemical performance indicators) resulted in much reduced soil erosion. In addition, soils under organic management showed $<$75% soil loss compared to the maximum tolerance value in the region (the maximum rate of soil erosion that can occur without compromising long-term crop productivity or environmental quality -11.2 t ha^{-1} yr^{-1}), while in conventional soil a rate of soil loss three times the maximum tolerance value was recorded.

As a result of the Rodale Institute Farming System Trial, Pimentel *et al*. (2005) reported that after 22 years the increase of SOM was significantly higher in both organic animal and organic legumes systems, where soil carbon increase by 27.9% and 15.1% respectively, when compared to the conventional system, where the increase was 8.6%. Moreover, soil Carbon (C) level was 2.5% in organic animal, 2.4% in organic legume and 2.0% in the conventional system.

In a 12-year trial in Maryland, Teasdale *et al*. (2007) found that organic farming can provide greater long-term soil benefits than conventional farming with no tillage, despite the use of tillage in organic management. A drawback of the organic system was the difficulty in controlling weeds, explained by the authors by a number of factors such as short crop rotation and remaining crop residues (Teasdale *et al*., 2007; Cavigelli *et al*., 2008). However, the authors argue that despite poor weed control, the organic systems improved soil productivity significantly as measured by corn yields in a uniformity trial conducted in the American Mid-Atlantic region. The same study also indicates that supplying adequate nitrogen (N) for corn and controlling weeds in both corn and soybean are the biggest challenges to achieving equivalent yields between organic and conventional cropping systems (Cavigelli *et al*., 2007). SOM increase for organic soil has been reported also by Marriott and Wander (2006) in a long-term U.S. trial.

In the longest trial so far (running for more than 150 years), and going on at the Rothamsted Experimental Station in the UK, SOM and soil total N levels have been reported to have increased by about 120% over 150 years in the organic manured plots, and only by about 20% in the plots employing NPK fertilizer. Yields for organic wheat have averaged 3.45 t ha^{-1} on organically manured plots, compared with 3.40 t ha^{-1} on plots receiving NPK (Tilman, 1998). Long-term trials in Poland (Stalenga and Kawalec, 2008) also report consistent increase of SOM under organic management.

Different findings have also been reported. In an 18-year-long study in Sweden, Kirchmann *et al*. (2007, did not find significant differences in soil carbon for organic systems compared to conventional systems. It is to be considered that some can be increased up to a certain level where it starts leveling-off.

B. Soil Chemical Properties

In an 8-year experiment in the California's Sacramento Valley, Clark *et al*. (1998) found that the transition from conventional to organic farming improved soil fertility by increasing soil organic C and the pools of stored nutrients. In Europe, a 21-year Swiss field study on loess soil analyzed the agronomic and ecological performance of biodynamic, organic, and conventional farming systems (Siegrist *et al*., 1998; Mäder *et al*., 2002a; Fließbach *et al*., 2007). The authors found that the aggregate and percolation stability of both bio-dynamic and organic plots were 10 to 60% higher than conventionally farmed plots. This also affected the water retention potential of these soils in a positive way and reduced their susceptibility to erosion. Soil aggregate stability was strongly correlated to earthworm and microbial biomass, important indicators of soil fertility (Mäder *et al*., 2002a). The long-term application of organic manure positively influenced soil fertility at the biological, chemical and physical level, whereas the repeated spraying of pesticides appeared to have negative effects. Compared to stockless conventional farming (mineral fertilizers, herbicides and pesticides), the aggregate stability in plots with livestock-based integrated production (mineral and organic fertilizers, herbicides and pesticides) was 29.4% higher, while in organic and bio-dynamic plots (organic fertilizers only) was 70% higher. The authors underline the importance of using manure, by means of organic agriculture, as a good practice for soil quality preservation (Fließbach *et al*., 2007). In addition, planting cover crops once the crop is harvested helps prevent soil erosion, as the soil is kept covered with vegetation all year long.

In North Carolina, Liu *et al*. (2007) found that soils from organic farms had improved soil chemical factors and higher levels of extractable C and N, higher microbial biomass carbon and nitrogen, and net mineralizable N. In Italy, Russo *et al*., (2010) comparing chemical and organic N uptake by crops, found that altogether more mineral N was released in soil and water from the organic fertilizer while more N was taken up by plants with the mineral fertilizer. While microbial population in the soil was unaffected by the type and amount of fertilizers, enzymatic activity responded positively to organic N and was depressed by the synthetic N form. According to Walden *et al*. (1998), organically managed soils may also use mineral nutrients in a more efficient manner and allow lower inputs.

C. Nitrogen Leaching

Nitrogen fertilizers are of key importance in intensive conventional agriculture. However, their use turns out to be a major cause of concern when coming to environmental pollution. The primary source of N pollution comes from N-based agricultural fertilizers, whose use is forecast to double or almost triple by 2050 (Tilman *et al*., 2001; Robertson and Vitousek, 2009; Vitousek *et al*., 2009).

A proportion of soluble N leaches deep into groundwater, ultimately affecting human health, whereas other soluble N volatilizes (e.g., NO_X) to increment GHGs. Considering that nitrous oxide is the most potent GHG and given the environmental problems associated with the production and use of synthetic fertilizer, there is a great need for researchers concerned with global climate change and nitrate pollution to evaluate reduction strategies (Tilman *et al.*, 2002; Millenium Ecosystem Assessment, 2005a; Robertson and Vitousek, 2009; Vitousek *et al*., 2009).

On average, agricultural system N balances (N input vs. N removed with crops) in the developed or rapidly developing worlds are positive (200–300 kg N yr^{-1}), implying substantial losses of N to the environment. A number of practices can be implemented in order to reduce N loss. In this regard, leguminacae can be used productively as cover crops, absorbing N through N_2 fixation and building SOM, and in some cases can also be used by intercropping. The development of crop varieties with higher efficiencies of N uptake could help capture more of the N added to annual cropping systems (e.g., Robertson and Vitousek, 2009; Vitousek *et al*., 2009). Techniques to reduce N loss and to increase the efficiency of N uptake are widely used in organic farming (Drinkwater *et al*.,1998; Lampkin, 2002; Kramer *et al.*, 2006), and many trials demonstrate the benefit of organic farming in reducing N leaching and increasing N uptake efficiency.

A 9-year trial has been conducted by Kramer *et al.* (2006) in commercial apple orchards in Washington State, USA. The study examined denitrification and leaching from organic, integrated, and conventional systems receiving the same amount of N inputs but in different forms. The authors found that annual nitrate leaching was 4.4–5.6 times higher in conventional plots than in organic plots, where microbial denitrifier activity is enhanced through C inputs as organic fertilizers, crop residues, or root exudates from cover crops. Integrated plots showed, intermediate leaching, somewhere between organic and conventional plots. This study demonstrates that organic and integrated fertilization practices support more active and efficient denitrifier bacterial communities and reduce environmentally damaging nitrate losses.

Drinkwater *et al*. (1998) reported better N uptake efficiency for organic systems, and argued that there are differences in the partitioning of nitrogen from organic versus mineral sources, with more legume-derived nitrogen than fertilizer-derived nitrogen immobilized in microbial biomass and SOM, so reducing leaching of NO_3^- of 60% compared to the conventional control. Küstermann *et al.* (2010) report a reduction of N loss in organic farming, compared with the conventional system. An 18-year field study in Swedenby Kirchmann *et al.* (2007) reports different results. The authors found that N leaching is not reduced in organic farming, even with use of cover crops. The authors argue that yield and soil fertility were superior in conventional cropping systems under cold-temperate conditions.

Possible drawbacks from organic fertilization have been reported by some authors (e.g., Tilman *et al*., 2002; Sieling and Kage, 2006; Kirchmann *et al*., 2007; Wu and Sardo, 2010): the ‘slow release’ of nutrients from organic compost or green manures can be difficult to control and harness and may fail to match crop demand, resulting in N losses through leaching and volatilization. Moreover, in organic systems, competition with weeds can greatly reduce N intake efficiency (Kirchmann *et al*., 2007).

Atmospheric nitrous oxide (N_2O) is a greenhouse gas nearly 300 times more effective at radiative warming than CO_2, and is produced mainly during the microbially mediated process of denitrification. There has been a marked increased in atmospheric N_2O over the past 150 years; about 80% of this source is associated with agriculture, largely (50%) with fertilized soils (Tilman *et al*., 2001; Robertson and Vitousek, 2009; Vitousek *et al*., 2009). Although N_2O contributed for only about 6% to of the global waring potential, it plays a substantial role in the agricultural contribution to climate change, and its emissions can offset efforts to use agricultural systems to mitigate climate change by sequestering CO_2 or providing alternative energy sources (Robertson and Vitousek, 2009)

Works by Mathieu *et al.* (2006) support the hypothesis that an increase in soil available organic carbon leads to N_2 emissions as the end product of denitrification, whilst Petersen *et al.* (2006), in a study concerning five European countries, found that N input is a significant determinant for N_2O emissions from agricultural soils, and that N_2O emissions from conventional crop rotations were higher than those from organic crop rotations (except in Austria), with significant differences between locations and crop categories. Stalenga and Kawalec (2008) found that N_2O emission for organic farming systems was about 66% lower than conventional systems and 50% lower than integrated systems.

In a long-term study in southern Germany, Flessa *et al.* (2002) also found reduced N_2O emission rates in organic agriculture, although yield-related emissions were not reduced. Contrasting result are reporter by Bos *et al.* (2006, in Niggli *et al.*, 2009) with a reduction of the GHGs on Dutch organic dairy farms and in organic pea production areas, and higher GHGs emissions for organic vegetable crops (e.g., leek and potato).

TABLE 1
The Rodale Institute Farming System Trial, crops performance under drought condition, data after Pimentel *et al.* (2005).

	Yield (kg ha^{-1})	
Farming system	Corn	Soybean
Organic animal	1, 511	1, 400
Organic legume	412	1, 800
Conventional	1, 100	900

D. Water Use and Resistance to Drought

Water use efficiency is determined by the amount of crop yielded divided by the amount of water used (Stanhill, 1986; Morison *et al.*, 2008). Several ways to improve water use efficiency in organic agriculture have been proposed, including reducing evaporation through minimum tillage, mulching, using more water-efficient varieties and inducing microclimatic changes to reduce crop water requirements (Stanhill, 1986; Pretty *et al.*, 2006; Morison *et al.*, 2008). Sustainable agricultural practices can be effective in improving water use efficiency in particular in poor developing country affected by water scarcity (Pretty *et al.*, 2006). Organic farming proves to be effective both at enhancing soil water content and improve water use efficiency.

Long-term crop yield stability and the ability to buffer yields through climatic adversity will be critical factors in agriculture's capability to support society in the future. A number of studies have shown that, under drought conditions, crops in organically managed systems produce higher yields than comparable crops managed conventionally. This advantage can result in organic crops out-yielding conventional crops by 70–90% under severe drought conditions (Lockeretz *et al.*, 1981; Stanhill, 1990; Smolik *et al.*, 1995; Teasdale *et al.*, 2000; Lotter *et al.*, 2003; Pimentel *et al.*, 2005). According to Lotter *et al.* (2003), the primary mechanism for higher yields in organic crops is due to higher water-holding capacity of soils under organic management. Others studies have shown that organically managed crop systems have lower long-term yield variability and higher cropping system stability (Smolik *et al.*, 1995; Lotter *et al.*, 2003).

As part of the Rodale Institute Farming System Trial (from 1981 to 2002), Pimentel *et al.*, (2005) found that during 1999, a year of extreme drought, (with total rainfall between April and August of 224 mm, compared with an average of 500 mm) the organic animal system had significantly higher corn yield (1,511 kg per ha) than either organic legume (412 kg per ha) or the conventional (1,100 kg per ha) systems.

For soybean both organic systems performed much better than the conventional system (Table 1).

Pimentel *et al.* (2005) estimated the amount of water held in the organic plots of the Rodale experiment in the upper 15 cm of soil at 816.000 liters per ha. In heavy loess soils in a temperate climate in Switzerland water holding capacity was reported being 20 to 40% higher in organically managed soils than in conventional ones (Mäder *et al.,* 2002a).

The primary reason for higher yield in organic crops is thought to be due to the higher water-holding capacity of the soils under organic management (Reganold *et al.*, 1987; Sullivan, 2002; Lotter *et al.*, 2003). Soils in the organic system capture more water and retain more of it, up to 100% higher in the crop root zone, when compared to conventional. Such characteristics make organic crop management techniques a valuable resource in this present period of climatic variability, providing a better buffer to environmental extremes, especially in developing countries.

A soil's texture (the proportions of sand, silt, and clay present in a given soil), and aggregation (how the sand, silt, and clay come together to form larger granules) determine air and water circulation, erosion resistance, looseness, ease of tillage, and root penetration. Texture is a given property of the native soil and does not change with agricultural activities. Aggregation, however, can be improved or weakened through the timing of farm practices. Among the practices that destroy or degrade soil aggregates are: excessive tillage, tilling when the soil is too wet or too dry, using anhydrous ammonia (because it speeds the decomposition of organic matter), using excessive nitrogen fertilization, or using salty irrigation water or sodium-containing fertilizers, which results in the excessive buildup of sodium (Sullivan, 2002). It has been estimated that for every 1% of SOM content, the soil can hold 10.000-11.000 liters of plant-available water per ha of soil down to about 30 cm (Sullivan, 2002).

However, it has to be pointed out that local specificity plays an important role in determining the performance of a farming system: what is sustainable for one region may not be for another region or area (Smolik *et al.*, 1995). So, more work has to be done to acquire knowledge about the comparative sustainability of different farming systems.

Adaptive measures to cope with climate change should treasure knowledge gained from organic farming. Extensive experimentation should be conducted to gain better understating of the complex interaction among farming practices, environmental characteristics and agroecosystem resilience.

E. The Potential for Organically Managed Farming Systems to Operate as a Carbon Sink and Contribute to GHGs Reduction

Annual fossil CO_2 emissions increased from an average of 6.4 Gt C (or 23.5 Gt CO_2) per year in the 1990s to 7.2 Gt C (or 26.4 GtCO_2) per year in 2000–2005. CO_2 emissions associated with land-use change are estimated to average 1.6 GtC (5.9 GtCO_2) per year over the 1990s, although these estimates have a large uncertainty (IPCC, 2007).

Agricultural activities (not including forest conversion) account for approximately 5% of anthropogenic emissions of CO_2 and the 10–12% of total global anthropogenic emissions of GHGs (5.1 to 6.1 Gt CO_2 eq. yr^{-1} in 2005), accounting for nearly all the anthropogenic methane and one to two thirds of all anthropogenic nitrous oxide emissions are due to agricultural activities (IPCC, 2000, 2007).

In 2008, in the United States, agricultural activities were responsible for about 7% of total U.S. GHGs emissions in 2008 (with livestock as major contributors) with an increase of 10% from 1998 to 2008 (U.S. EPA, 2010).

According to Smith *at al*. (2008) many agricultural practices can potentially mitigate GHG emissions, such as: improved cropland and grazing land management, restoration of degraded lands and cultivated organic soils; and point out that the current levels of GHG reduction are far below the technical potential of these agricultural practices. Smith *et al*. (2008) estimate that agriculture could offset, at full biophysical potential, about 20% of total global annual CO_2 emissions.

Some authors (Kern and Johnson, 1993; Schlesinger, 1999) report that converting large areas of U.S. cropland to conservation tillage (including no-till practices), could sequester all the CO_2 emitted from agricultural activities in the United States, and up to 1% of today's fossil fuel emissions in the United States. Similarly, alternative management of agricultural soils in Europe could potentially provide a sink for about 0.8% of the world's current CO_2 release from fossil fuel combustion.

Lal (2004) has estimated that the strategic management of agricultural soil that is moving from till to no-till farming (also known as *conservation tillage, zero tillage,* or *ridge tillage*) has the potential to reduce fossil-fuel emissions by 0.4 to 1.2 Gt C yr^{-1}. This equals to a reduction of 5% to 15% of global CO_2 emissions.

In a 10-year systems trial in American Midwest, Grandy and Robertson (2007) found that compared to conventional agriculture, increases in soil C concentrations from 0 to 5 cm occurred with no-till (43%), low input (17%) and organic (24%) management. Soil carbon fixation is possible for conventional agriculture ranging from 8.9 gC m^{-2} y^{-1} (0.89 t ha^{-1} y^{-1}) in row crops to 31.6 gC m^{-2} y^{-1} (3.16 t ha^{-1} y^{-1}) in the early successional forage crops. Reduction in land use intensity increases soil C accumulation in soil aggregates. The authors argue that soil tillage is of key importance to determine soil C accumulation and suggest that there is high potential for carbon sequestration and offsetting atmospheric CO_2 increases by effective management of agriculture land.

Evidence from numerous long-term agroecosystem experiments indicates that returning residues to soil, rather than removing them, converts many soils from "sources" to "sinks" for atmospheric CO_2 (Rasmussen *et al*., 1998; Lal, 2004; Smith *et al*., 2008).

Properly managed agriculture and SOM increase in cultivated soil play an important role in the storage of carbon, and this has been addressed by many authors (e.g., Janzen, 2004; Drinkwater *et al*., 1998; Stockdale *et al*., 2001; Pretty *et al*., 2002; Holland, 2004; Lal, 2004; Pimentel *et al*., 2005; IPCC, 2007; Smith *et al*., 2008). This carbon can be stored in soil by SOM and by aboveground biomass through processes such as adopting rotations with cover crops and green manures to increase SOM, agroforestry, and conservation-tillage systems. According to a review carried out by Pretty *et al*. (2002), carbon accumulated under improved management increased by more than 10 times, from 0.3 up to 3.5 tC ha^{-1} yr^{-1}.

Organic agriculture practices play an important role in enhancing carbon storage in soil in the form of SOM. Results from a 15-year study in the United States, where three district maize/soybean, two legume-based and one conventional agroecosystems were compared, led Drinkwater *et al*. (1998) to estimate that the adoption of organic agriculture practices in the maize/soybean grown region in the U.S. would increase soil carbon sequestration by 0.13 to 0.30 10^{14} g yr^{-1}. This is equal to 1–2% of the estimated carbon released into the atmosphere from fossil fuel combustion in the USA (referring to 1994 figures of 1.4 10^{15} g yr^{-1}).

Both because there is a limit to how much carbon the soil can capture acting as a carbon sink and because fossil fuels are being used at a very rapid pace, conversion to organic agriculture only represents a temporary and partial solution to the problem of carbon dioxide emissions Foereid and Høgh-Jensen (2004) developed a computer model for organic agriculture acting as carbon sink, and simulations show a relatively fast increase in the first 50 years, by 10–40 g C m^{-2} y^{-1} on average; this increase would then level off, and after 100 years reach an almost stable level of sequestration.

Although organic agriculture may represents an important option to reduce CO_2, long-term solutions concerning CO_2 and GHGs emission abatement should rely on a more general change of our development path, for instance by reducing overall energy consumption.

F. Soil Ecology, Biodiversity, and Its Effects on Pest Control

One hectare of high-quality soil contains an average of 1,300 kg of earthworms, 1,000 kg of arthropods, 3,000 kg of bacteria, 4,000 kg of fungi, and many other plants and animals (Pimentel *et al*., 1992; Lavelle and Spain, 2002). Transition to organic soil management can benefit soil biodiversity. In this context, it should also be noted that SOM play an essential role in increasing soil biodiversity (Pimentel *et al.*, 2006).

Enhancement of soil microbes and soil microfauna by organic inputs has been demonstrated in alternative farming systems across different climatic and soil conditions (Paoletti *et al.*, 1995, 1998; Gunapala and Scow, 1998; Fließbach and Mäder, 2000; Hansen *et al.*, 2001; Mäder *et al.*, 2002a; Marinari *et al.* 2006; Tu *et al.*, 2006; Briar *et al.*, 2007 Fließbach *et al.*, 2007; Liu *et al.*, 2007; Birkhofer *et al.*, 2008; Phelan, 2009).

Hansen *et al.* (2001), reviewing several studies on soil biology, found that organic farming is usually associated with a significantly higher level of biological activity, represented by bacteria, fungi, springtails, mites and earthworms, due to its versatile crop rotations, reduced applications of nutrients, and the ban on pesticides.

In a Swiss long-term experiment (Siegrist *et al.*, 1998; Mäder *et al.*, 2002a; Fließbach *et al.*, 2007), soil ecological performance were greatly enhanced under biodynamic and organic management.

Microbial biomass and activity increased under organic management, root length colonized by mycorrhizae in organic farming systems was 40% higher than in conventional systems. Biomass and abundance of earthworms were from 30 to 320% higher in the organic plots as compared with conventional. Although the number of species of carabid beetles were not significantly higher in organic and biodynamic system compared to conventional (28–34 in biodynamic; 26–29 in organic and 22–26 in conventional), still some specialized and endangered species were reported to be present only in the two organic systems.

Concerning soil health, Briar *et al.* (2007) conclude that transition from conventional to organic farming can increase soil microbial biomass, N and populations of beneficial bacterivore nematodes while simultaneously reducing the populations of predominantly plant-parasitic nematodes. The authors also indicate that reducing tillage provides benefits for the development of a more mature soil food web.

In a seven-year experiment in Italy, Marinari *et al.* (2006) compared two adjacent farms, one organic and one conventional, and found that the fields under organic management showed significantly better soil nutritional and microbiological conditions; with an increased level of total nitrogen, nitrate and available phosphorus, and an increased microbial biomass content, and enzymatic activities.

Liu *et al.* (2007) report that in North Carolina microbial respiration in soils from organic farms was higher than that in low-input or conventional farms, indicating that microbial activity was greater in these soils, and that populations of fungi and thermophiles were significantly higher in soils from organic and low-input when compared to those of conventional fields.

Birkhofer *et al.* (2008) found that organic farming fosters microbial and faunal decomposers and this propagates into the aboveground system, sustaining a higher number of generalist predators, thereby increasing natural pest control. The authors, however, note that grain and straw yields were 23% higher in systems receiving mineral fertilizers and herbicides then the organic systems.

Soil management also seems to affect pest response. A number of studies report pest preferring plants which have been nurtured with synthetic fertilizer rather than those growing in organically managed soil (Phelan *et al.*, 1995, 1996; Alyokhin *et al.*, 2005; Hsu *et al.*, 2009). This is explained by the "mineral balance hypothesis" (Phelan *et al.*, 1996), which states that organic matter and microbial activity associated with organically managed soils allow to enhance nutrient balance in plants, which in turn can better respond to pest attack. Phelan and colleagues (Phelan *et al.*, 1995; 1996; Phelan, 2009) report that under green house controlled experiments, females of European corn borer (*Ostrinia nubilalis*) were found to lay consistently fewer eggs in corn on organic soil than on conventional soil. Research on the effect of butterfly *Pieris rapae crucivora,* a cabbage pest, by Hsu *et al.* (2009) indicated that these butterflies preferred to lay eggs on foliage of synthetically fertilized plants (authors argue that proper organic fertilization can increase plant biomass production and may result lower pest incidence). Moreover, Alyokhin *et al.* (2005) reported that densities of Colorado potato beetle (*Leptinotarsa decemlineata*) were generally lower in plots receiving manure soil amendments in combination with reduced amounts of synthetic fertilizers compared to plots receiving full rates of synthetic fertilizers, but no manure.

A more complex relation between soil fertilization and crop pest has been found by Staley *et al.*, (2010). The authors report that two aphid species showed different responses to fertilizers: the *Brassica* specialist *Brevicoryne brassicae* was more abundant on organically fertilized plants, while the generalist *Myzus persicae* had higher populations on synthetically fertilized plants. The diamondback moth *Plutella xylostella* (a crucifer specialist) was more abundant on synthetically fertilized plants and preferred to oviposit on these plants. The authors found also that glucosinolate concentrations were up to three times greater on plants grown in the organic treatments, while nitrogen content as maximized on plant foliage under higher or synthetic fertilizer treatments.

IV. BIODIVERSITY

Biodiversity refers to the number, variety and variability of living organisms in a given environment. It includes diversity within species, between species, and among ecosystems (Wilson, 1988; Gaston and Spicer, 2004; Koh *et al.*, 2004; Chivian and Bernstein, 2008). The concept also covers how this diversity changes from one location to another and over time. Biodiversity assessment, such as the evaluation of the number of species in a given area, or the more affordable use of bioindicators, can help in monitoring certain aspects of biodiversity (Paoletti, 1999; Büchs, 2003; Duelli and Obrist, 2003; Paoletti *et al.*, 2007a), even if due attention should be paid to the comparison procedure (Gotelli and Colwell, 2001; Duelli and Obrist, 2003; Pocock and Jennings, 2007). Within the term biodiversity also fall the biodiversity of crops and reared animals and the management strategy of the farm itself (e.g., rotation pattern, intercropping) (Lampkin, 2002; Caporali *et al*., 2003; Noe *et al*., 2005; Norton *et al*., 2009)

The most dramatic ecological effect of agriculture expansion on biodiversity has been habitat destruction, which, along with soil erosion and the intensive use of agrochemicals (e.g., pesticides and fertilizers), has combined to threaten biodiversity (Paoletti and Pimentel, 1992; Pimentel *et al*., 1995; Krebs *et al*., 1999; Benton *et al*., 2003; Foley *et al*., 2005; Pimentel *et al*., 2006; Butler *et al*., 2007; Paoletti *et al*., 2007b). According to Czech *et al*. (2000), in the United States agriculture has contributed to endangering biodiversity more than any other cause except urbanization.

Organic farming can offer a possible solution to halt, or reduce, biodiversity loss by a number of means such as preservation of ecological elements of the landscape, reduction in the use of harmful chemicals and alleviation of stress caused on soil ecology.

A. Organic Farming and Biodiversity

Whether organic agriculture enhances biodiversity has been a matter of research and debate for the last decades (Paoletti and Pimentel, 1992; Moreby *et al*., 1994; Stockdale *et al*., 2001; Shepherd *et al*., 2003; Bengtsson *et al*., 2005; Fuller *et al*., 2005; Hole *et al*., 2005; Hyvönen, 2007; Norton *et al*., 2009).

Extensive analysis (e.g., Moreby *et al*., 1994; Pfiffner and Niggli, 1996; Mäder *et al.*, 2002a; Caporali *et al*., 2003; Bengtsson *et al.*, 2005; Fuller *et al*., 2005; Hole *et al*., 2005; Roschewitz *et al.*,2005; Gabriel *et al*., 2006, 2010; Clough *et al*., 2007a; Hyvönen, 2007; Hawesa *at al.*, 2010), suggest that organic farming is generally associated with higher levels of biodiversity with regards to both flora and fauna.

A wide meta-analysis by Bengtsson *et al*. (2005) indicated that organic farming often has positive effects on species richness and abundance: 53 of the 63 studies analyzed (84%) showed higher species richness in organic agriculture systems, but a range of effects considering different organism groups and landscapes. Bengtsson *et al*. (2005) suggest that positive effects of organic farming on species richness can be expected in intensively managed agricultural landscapes, but not in small-scale landscapes comprising many other biotopes as well as agricultural fields. A review of the literature carried out by Hole *et al*. (2005) confirms the positive effect of organic farming on biodiversity, but authors point out that such benefits may be achieved also by conventional agriculture when carefully managed (a finding that seems supported also by other authors, e.g., Gibson *et al*., 2007), and indicate the need for long term, system-level studies of the biodiversity response to organic farming.

Comparing local weed species diversity in organic and conventional agriculture in agricultural areas in Germany, Roschewitz *et al*. (2005) found that weed biodiversity was influenced by both landscape complexity and farming system. The authors reported that local management (organic vs. conventional) and complexity of the surrounding landscape had an influence on alpha, beta and gamma diversities of weeds in 24 winter wheat fields. Species diversity under organic farming systems was clearly higher in simple landscapes, but conventional vegetation reached similar diversity levels when the surrounding landscape was richer because of the presence of refugia for weed populations. Roschewitz *et al*. (2005) argue that agri-environment schemes designed to preserve and enhance biodiversity should not only consider the management of single fields but also that of the surrounding landscape. Along similar lines, in Finland, Hyvönen *et al*. (2003) studied diversity and species composition of weed communities during spring in cereal fields cultivated by organic, conventional cereal and conventional dairy cropping, and concluded that organic cropping tends to promote weed species diversity at an early phase of cropping history, in particular for species susceptible to herbicides. The authors, however, argue that a change in species composition would require a longer period of organic cropping. In Scotland, Hawesa *at al.* (2010) found significantly more weeds in the seedbank and emerged weed flora of organic farms compared to either integrated or conventional farms and concluded that organic systems tend to support a greater density, species number and diversity of weeds compared to conventional management.

It has been demonstrated that when farming management is turned from conventional to organic, the weed populations can be restored to a state comparable to that before application of intensive cropping measures (Hyvönen and Salonen, 2002; Hyvönen, 2007). However, the recovery of the weeds is reported to differ between species, with species with a more rapid recovery being nitrophilous species that suffered from the application of herbicides, or species that were tolerant against herbicides. Perennial species favored by grasslands showed the slowest recovery. The authors point out that application of diverse crop rotations in organic cropping is the focal factor affecting species composition of weed communities.

Pfiffner *et al.* (2001) conducted a review of 44 investigations worldwide concerning the effects of organic and conventional farming on fauna, and reported organic farming as performing much better on both organism abundance and species diversity.

In Swiss trials (Pfiffner and Niggli, 1996; Mäder *et al.*, 2002a; Pfiffner and Luka, 2003), earthworms, carabids, epigeal spiders and other epigeal arthropods have been reported to be more abundant and with higher biodiversity in organic/biodynamic fields compared to conventional fields. They suggest the higher abundance might depend upon low-input and organic fertilization, more favorable plant biota protection management (especially weed management) and possibly upon closer interaction with semi-natural habitats.

Ekroos *et al*. (2010), comparing both weed and carabid beetles biodiversity, find that, in the case of weds, organic farming increased both insect-pollinated as well as overall weed species richness, whereas the proportion of insect-pollinated weed species within the total species richness was unaffected by farming practices; on the other hand, in the case of carabid beetles a positive correlation with organic farming was less evident. Pfiffner and Niggli (1996) reports higher diversity and abundance of carabid beetles (90% greater) and other epigeic arthropods on organic plots of winter wheat than in conventional plots. Research carried out in North Eastern Italy in different types of orchards and vineyards found that arthropods, carabid species and earthworms were more abundant in organic than in conventional agroecosystems (Paoletti *et al*., 1995, 1998). Greater abundance of earthworms (up to more than 100%) and insects for organic farms has been reported also for Swiss farming system (Pfiffner and Mäder, 1997; Pfiffner and Luka, 2007).

In the largest and most comprehensive study of organic farming in the UK to date, Fuller *et al*. (2005) shows that organic farms provide greater benefits for a range of wildlife (including wild flowers, beetles, spiders, birds and bats) than their conventional counterparts. Fuller *et al*., (2005) found that organic fields were estimated to hold 68–105% more plant species and 74–153% greater abundance of weeds (measured as cover) than nonorganic fields support, 5–48% more spiders in preharvest crops, 16–62% more birds in the first winter and 6–75% more bats (see also Wickramasinghe *et al.,* 2004, who have found that organic farming is beneficial to bats, both through provision of more structured habitats and higher abundance of insect prey). These studies indicate that organic farming systems provide greater potential for biodiversity than their conventional counterparts, as a result of greater variability in habitats and more wildlife-friendly management practices, which results in real biodiversity benefits, particularly for plants. Plants indeed showed far more consistent and pronounced responses to the use of organic systems when compared to other taxa, as reported also by Bengtsson *et al*. (2005).

In the case of other taxa, Fuller *et al*. (2005) report that even where significant differences were detected, the results showed high variability and wide confidence intervals. Compared to the review by Bengtsson *et al*. (2005), Fuller *et al*. (2005) in their meta-analysis find that predatory invertebrates showed a significant response to agricultural practices only infrequently.

Results from Swedish research on butterfly species diversity in organic and conventional farms (Rundlöf and Smith, 2006; Rundlöf *et al*., 2008) indicate that both organic farming and landscape heterogeneity significantly increased butterfly species richness and abundance. Authors report also that there was a significant interaction between farming practice and landscape heterogeneity, and organic farming significantly increased butterfly species richness and abundance only in homogeneous rather than heterogeneous landscapes.

A previous Swedish study (Weibull *et al*., 2003) did not find differences when comparing the biodiversity and abundance of plants, butterflies, rove beetles and spiders in organic and conventional farms, while carabids richness was higher in conventional farms. The authors argued that species richness was higher on farms with a heterogeneous landscape, while farming practice was of relatively less importance in relation to landscape features for species richness.

A review of literature on carabid beetles in organic and conventional farming system in Germany and Switzerland by Döring and Kromp (2003) found that in most cases species richness was higher in the organically than in the conventionally managed fields.

No difference for carabids biodiversity were instead reported by the USDA Farming Systems Project in Maryland, by Clark *et al*. (2006) in organic, no-till, and chisel-till cropping systems.

According to van Elsen (2000), economic pressure leads to an improvement in mechanical weed control and undersowing, so that supporting and developing a diverse arable field flora cannot be done automatically just by converting to organic farming. Rather, an integration with the guiding vision of organic agriculture is needed, and measures to support the richness of species of arable field plants in organic fields have to be developed.

B. Biodiversity and Landscape

An increasing body of evidence indicates that landscape heterogeneity is a key factor in promoting biodiversity in the agricultural landscape (Benton *et al.*, 2003; Purtauf *et al*., 2005; Schmidt *et al*., 2005; Tscharntke *et al*., 2005; Gabriel *et al.*, 2006, 2010; Rundlöf and Smith, 2006; Clough *et al*., 2007b; Norton *et al*., 2009). A mosaic landscape may support a larger number of species in a given area, simply because the landscape contains a larger number of habitats. Organic farming system produced greater field and farm complexity than farms employing a nonorganic system (Gabriel *et al.,* 2006, 2010; Clough *et al.*, 2007b; Norton *et al*., 2009). In Germany, Gabriel *et al.* (2006, 2010) found that plant species in wheat organic farming made the greatest contribution to total species richness at the meso (among fields) and macro (among regions) scale due to environmental heterogeneity. Rundlöf and Smith (2006) argue that organic farming, with its exclusion of pesticides and longer crop rotation, may, on a landscape scale, increase habitat heterogeneity and biodiversity.

Some scholars argue that because many organic farms are often isolated units, embedded in nonorganic farmland managed with conventional levels of pesticide and fertilizer inputs, offering a relatively low levels of habitat heterogeneity, this may reduce the benefits offered by organic farming as well as by species colonization. In these cases, organic farming probably offer insufficient resources to affect population sizes of species with large spatial needs, such as birds (Bosshard *et al*., 2009; Brittain *et al*., 2010).

Concerning invertebrates, agricultural landscapes with organic crops have overall been reported to support higher biodiversity for pollinator (Holzschuh *et al*., 2008), butterfly (Rundlöf and Smith, 2006), carabid beetle (Purtauf *et al*., 2005), spiders (Fuller *et al*., 2005; Schmidt *et al.*, 2005), and a number of invertebrates taxa (Benton *et al*., 2003; Bengtsson *et al*., 2005; Clough *et al*., 2007). It has to be pointed out that the extent of non-crop habitat in the vicinity of organic farms (usually larger than for conventional farms) is likely to be beneficial for biodiversity (Holzschuh *et al*., 2007; Norton *et al*., 2009). Holzschuh *et al.* (2007), for instance, found that landscape heterogeneity and the availability of semi-natural nesting habitats resulted in higher bee diversity on farmland.

It would appear that the extension of organic farming is a potential means of reestablishing heterogeneity of farmland habitats, and thereby enhancing farmland biodiversity. However, the total area of organic farmland relative to nonorganic is generally small (a few points percentage of the total agricultural area per country). Strategies aimed at increasing both the total extent of organic farming and the size and contiguity of individual organic farms could help to restore biodiversity in agricultural landscapes (Fuller *et al*., 2005; Tscharntke *et al*., 2005; Bosshard *et al*., 2009). This strategy is supported also by other authors. Benton *et al.* (2003) for instance, argue that, rather than concentrating on particular farming practices, promoting heterogeneity widely across agricultural systems should be a universal management objective.

Given the body of evidence accumulated so far, it is clear that measures to preserve and enhance biodiversity in agroecosystems should be both landscape and farm specific (e.g., Paoletti, 1999; Thies and Tscharntke, 1999; Hole *et al*., 2005; Pimentel *et al*., 2005; Roschewitz *et al*., 2005; Tscharntke *et al*., 2005; Gabriel *et al.*, 2006, 2010; Rundlöf and Smith, 2006; Holzschuh *et al*., 2008; Norton *et al*., 2009). Unfortunately, it is difficult to provide reliable recommendations concerning agricultural land management in order to enhance biodiversity and ecosystem services, because there is still little knowledge about the relation among agricultural land management, both at farm and at landscape level, and ecosystem services. (Tscharntke *et al*., 2005; Gabriel *et al.*, 2006, 2010).

C. Biodiversity and Pest Control

One key feature of agricultural intensification has been the increasing specialization in the production process, resulting in reduction in the number of crop and livestock species, leading to monoculture and intensive farming (Zhu *et al.*, 2000; Matson *et al*., 1997; Tscharntke *et al*., 2005). On the other hand, it has been demonstrated that increasing crop genetic diversity can play an important role in pest management and in controlling crop disease, as well as enhance pollination services and soil processes (Zhu *et al.*, 2000; Barberi, 2002; Hajjar *et al*., 2008). Zhu *et al.* (2000), for instance, demonstrated that crop heterogeneity is a possible way to solve the problem of vulnerability of monoculture crops to disease. Barberi (2002) argues that weed management should be tackled on a long time frame and needs deep integration with the other cultural practices, so as to optimize whole system control.

Agriculture intensification results also in a dramatic simplification of landscape composition and in a sharp decline of biodiversity. This also affected the functioning of natural pest control, as natural habitats provide shelter for a broad spectrum of natural species that operate as pest control for all crops (Pimentel *et al*., 1992; 1997; Kruess and Tscharntke, 1994; Pimentel, 1997; Thies and Tscharntke, 1999; Barbosa, 2003; Altieri and Nicholls, 2004; Perfecto *et al*., 2004; Bianchi *et al*., 2006; Crowder *et al*., 2010).

Preserving landscape-ecological structures (e.g., hedgerows, herbaceous strips, woodlot) means also preserving their function as a haven for beneficial organisms that can provide useful services to agriculture. On the contrary, reducing ecological structures and causing habitat fragmentation results in a significant reduction in local biodiversity and its impact in the biological control of pests (Kruess and Tscharntke, 1994; Sommaggio *et al*., 1995; Paoletti *et al.*, 1997; Thies and Tscharntke, 1999; Letourneau and Goldstein, 2001; Thies *et al.*, 2003, 2005; Bianchi *et al*., 2006; Gardiner *et al*., 2009).

Letourneau and Bothwell (2008) argue that few studies have measured biodiversity effects on pest control and yield on organic farms compared to conventional farms, while relevant studies suggest that an increase in the diversity of insect predators and parasitoids can have both positive and negative effects on prey consumption rates. As mentioned earlier in this paper, Briar *et al*. (2007) reported the positive role of the transition from conventional to organic farming in increasing populations of beneficial bacterivore nematodes while reducing plant-parasitic nematodes.

Perfecto *et al*. (2004) found that in coffee farms in Chiapas, Mexico, birds could potentially reduce pest outbreak in farms with higher floristic diversity, thus providing partial evidence in support of the "insurance hypothesis." In organic cereal fields in Germany, Westerman *et al*. (2003) found that seed predation by birds contributes substantially to the containment of weed population growth.

Other experiments proved the role of vegetation and bird presence in reducing pest outbreaks. Mols and Visser (2002, 2007), for instance, found that big tit (*Parus major* L.), a European cavity-nesting bird, reduces the abundance of harmful caterpillars in apple orchards by as much as 50 to 99%. In the Netherlands, the foraging of *P. major* increased apple yields by 4.7 to 7.8 kg per tree.

Although some studies do not find a correlation between landscape complexity and parasitoid diversity (e.g., Menalled *et al*., 1999), most of them do confirm the importance of ecological structures for harbouring beneficial organisms. Research in Italy found that hedgerows in organic farming can improve consistently the number and abundance of invertebrates and can host important key species of predators and parasitoids that can provide a natural pest control for crops (Paoletti and Lorenzoni, 1989; Sommaggio *et al*., 1995; Paoletti *et al*., 1997). In an extensive experiment to assess the effectiveness of natural pest control provided to soybean by natural pest predators, 26 replicate fields were set across Michigan, Wisconsin, Iowa, and Minnesota over two years (2005–2006) (Gardiner *et al*., 2009). The authors found that the abundance of Coccinellidae was related to landscape composition, with beetles being more abundant in landscapes with an abundance of forest and grassland compared with landscapes dominated by agricultural crops. Landscape diversity and composition at a scale of 1.5 km surrounding the focal field explained the greatest proportion of variation in biological control service index (based on relative suppression of aphid populations and on Coccinellidae abundance). The authors conclude that management aimed at maintaining or enhancing landscape diversity has the potential to stabilize or increase biocontrol services.

Bianchi *et al.* (2006) reach the same conclusions. They find that enhanced natural enemy activity showed correlation with presence of herbaceous habitats such fallows and field margins (80% of cases), and also with presence of wooded habitats (71%), and of landscape patchiness (70%). The authors conclude that all these landscape characteristics are equally important in enhancing natural enemy populations, and claim that diversified landscapes hold most potential for the conservation of biodiversity and perform a pest control function.

It is often assumed that if the reduction in agrochemicals on organic farms allows the conservation of biodiversity, it on the other hand must have some cost in terms of increased pest damage. In an experiment in tomato farms in California, Letourneau and Goldstein (2001) tested such a claim. The authors found no evidence of increased crop loss when synthetic insecticides are withdrawn. The authors stress the importance of large-scale on-farm comparisons for testing hypotheses about the sustainability of agroecosystem management schemes and their effects on crop productivity and associated biodiversity.

Recently, Crowder *et al.* (2010) showed that such insecticides disrupt the communities of pest natural enemies, reducing the effectiveness of pest control. Authors claim that organic farming methods can mitigate this ecological damage by promoting evenness among natural enemies, implying that ecosystem functional rejuvenation requires restoration of species evenness, rather than just richness, and that organic farming can offer a means of reestablishing functional evenness to ecosystems. Bahlai *et al.* (2011), however, point out that organic pesticides may not represent always the best solution to mitigate environmental risk.

It has to be pointed out that biodiversity conservation, by retaining local food web complexity can also represent an effective management strategy against the spread of invasive species that often act as pests in new environments (Kennedy *et al.*, 2002). This may help to avoid the drawback from using exotic natural enemies to fight novel invasive species, as species introduced for biocontrol can act as invasive species in their own right (Thomas and Reid, 2007).

V. ENERGY USE AND GHGs EMISSION

A. Energy Efficiency

Organic farming has been reported to provide a better ratio of energy input/output (Table 2). (For further figures see also the review by Lynch *et al.*, 2011)

The main reasons for higher efficiency in the case of organic farming are: (1) lack of input of synthetic N-fertilizers (which require high energy consumption for production and transport and can account for more than 50% of the total energy input), (2) low input of other mineral fertilizers (e.g., P, K), lower use of highly energy-consumptive foodstuffs (concentrates), and (3) the ban on synthetic pesticides and herbicides (Lockeretz *et al.*, 1981; Pimentel *et al.*, 1983; 2005; Refsgaard *et al.*, 1998; Cormack, 2000; Stockdale *et al.*, 2001, Haas *et al.*, 2001; FAO, 2002; Lampkin, 2002; Hoeppner *et al.*, 2006; Kasperczyk and Knickel, 2006; Küstermann *et al.*, 2008; Lynch *et al.*, 2011). According to estimates carried out in a study conducted by the Danish government (Hansen *et al.*, 2001), upon 100% conversion to organic agriculture a 9–51% reduction in total energy use would ensue (the rate of reduction depending on the level of imported feeds and the numbers of animals reared).

However, when calculating energy input in terms of physical output units, a reduced advantage in employing organic systems was observed (Cormack, 2000; Stockdale *et al.*, 2001). On average, yield from arable crops is reported to be 20% to 40% lower in organic systems compared to conventional systems, whereas the yield for horticultural crops could be as low as 50% that of conventional; grass and forage production is reported between 0 and 30% lower for organic systems (Cormack, 2000; Stockdale *et al.*, 2001; Mäder *et al.*, 2002a, 2002b; Cavigelli *et al.*, 2007; Kirchmann *et al.*, 2007; Küstermann *et al.*, 2008).

Dalgaard *et al.* (2001) argue that the energy efficiency, calculated as the yield divided by the energy use (MJ ha^{-1}), was generally higher in the organic system than in the conventional system, but the yields were also lower. This meant that conventional crop production had the highest net energy production, whereas organic crop production had the highest energy efficiency.

In industrial societies, energy efficiency *per se* may not be the goal. Increasing productivity per hour of labor is in fact what modern society aims at, and this may lead us in the opposite direction (decreasing overall energy efficiency) (Giampietro, 2004). This inverse relation between total productivity and efficiency is typical for traditional agriculture and intensive agriculture. When comparing corn production in intensive U.S. farming systems and a Mexican traditional farming system the former had an efficiency (output/input) of 3.5:1 while the latter of 11:1 (using only manpower). However, when coming to total net energy production, intensive farming system accounted for 17.5 million kcal $ha^{-1}yr^{-1}$(24.5 in output and 7 in input), while traditional just 6.3 million kcal $ha^{-1}yr^{-1}$ (7 million in output and 0.6 million in input) (Pimentel, 1989).

On the other hand, some studies have found organic production comparable to that of conventional systems (Clark *et al.*, 1999; Pimentel *et al.*, 2005). Clark *et al.* (1999) argue that organic and low-input tomato systems can produce yields similar to those of conventional systems but that factors limiting yield may be more difficult to manage: N availability in the case of organic systems and water availability in that of conventionally managed systems. In the Rodale long-term study (Pimentel *et al.*, 2005) organic performance is comparable to conventional

TABLE 2
Comparison of energy efficiency (input/output) per unit of production of organic as percent of conventional farming systems.

Farming System	Reference	Energy Efficiency organic as % of conventional
Analysis for crops under organic and conventional management		
Wheat in USA	Pimentel *et al.* (1983)	+29/+70
Wheat in Germany (various studies)	Stölze *et al.* (2000)	+21/+43
Wheat in Italy	FAO (2002)	+25
Corn in USA	Pimentel *et al.* (1983)	+35/+47
Apples in USA	Pimentel *et al.* (1983)	−95
Potatoes in Germany (3 studies)	Stölze *et al.* (2000)	+7/+29
Potatoes USA	Pimentel *et al.* (1983)	−13/−20
Rotations of different crop systems in Iran	Zarea *et al.* (2000) (in FAO, 2002)	+81
Rotations of different crop systems in Poland	Kus and Stalenga (2000) (in FAO, 2002)	+35
Danish organic farming	Jørgensen *et al.* (2005)	+10
Whole system analysis (Midwest – USA) with comparable output	Smolik *et al.* (1995)	+60/+70
Crop rotations (wheat-pea-wheat-flax and wheat-alfalfa-alfalfa-flax) in Canada	Hoeppner *et al.* (2006)	+20
Apricot in Turkey	Gündomuþ (2006)	+53
Olive in Spain	Guzmán and Alonso (2008)	+50
Crop rotations	Küstermann *et al.* (2008)	+9
Results from Long-Term Agroecosystem Experiments		
Apples in USA	Reganol *et al.* (2001)	+7
Various crop systems	Mäder *et al.* (2002)	+20/+56%
Organic and animals	Pimentel *et al.* (2005)	+28
Organic and legumes	Pimentel *et al.* (2005)	+32
Organic vs. conv. with tillage	Gelfand *et al.* (2010)	+10
Organic vs. conv. no tillage	Gelfand *et al.* (2010)	−30

performance with respect to key agronomic indicators (Table 3).

As previously mentioned, it has to be pointed out that under drought conditions organic systems produce higher yields than comparable crops managed conventionally, up to 70–90% (Lockeretz *et al*., 1981; Stanhill, 1990; Smolik *et al*., 1995; Lotter *et al*., 2003; Pimentel *et al*., 2005).

It appears that the energetic performances of different farming systems depend on the crops cultured and specific farm characteristics (e.g., soil, climate). Pimentel *et al.* (1983), who reported lower energy efficiency in organic potatoes, ascribed it to reduced yield due to insect and disease attacks that could not be controlled in the organic system. In the case of apples there is a striking difference between data reported by Pimentel *et al*. (1983) and Reganold *et al*. (2001). This can be explained by different management techniques and their improvement in the last 20 years.

B. GHGs Emission

Agricultural contributions to CO_2 emissions come from consumption of energy in the form of oil and natural gas, both

TABLE 3
A comparison of the rate of return in calories per fossil fuel invested in production for major crops - average of two organic systems over 20 years in Pennsylvania (based on Pimentel, 2006, modified).

Crop	Technology	Yield (t ha^{-1})	Labor (hrs ha^{-1})	Energy (kcal x 10^6)	output/ input
Corn	*Organic*^{1}	*7.7*	*14*	*3.6*	*7.7*
Corn	Conventional^2	7.4	12	5.2	5.1
Corn	Conventional^3	8.7	11.4	8.1	4.0
Soybean	*Organic*^{4}	*2.4*	*14*	*2.3*	*3.8*
Soybean	Conventional^5	2.7	12	2.1	4.6
Soybean	Conventional^6	2.7	7.1	3.7	3.2

[1] Average of two organic systems over 20 years in Pennsylvania.
[2] Average of conventional corn system over 20 years in Pennsylvania.
[3] Average U.S. corn.
[4] Average of two organic systems over 20 years in Pennsylvania.
[5] Average conventional soybean system over 20 years in Pennsylvania.
[6] Average of U.S. soybean system.

directly (e.g., field work, machinery) and indirectly (e.g., production and transport of fertilizers and pesticides). Changes in soil ecology can also result in carbon release into the atmosphere. Deforestation is an important contributor to CO_2 emissions, occurring when forest land is removed to provide more land to plant crops. NH_4 emissions come from livestock, mainly from enteric fermentation but also from manure and rice fields. N_2O comes mainly from the soil (denitrification) and to a lesser extent from animal manure (IPCC, 2007). On the other hand, it is possible to reduce direct and indirect carbon emissions by reducing the use of agrochemicals, pumped irrigation and mechanical power, which account for most of the energy input in agriculture. It has also been suggested that organic farms can develop biogas digesters to produce methane for home and commercial use (Pretty *et al*., 2002; Hansson *et al*., 2007). This technology is, however, not limited to organic management.

Stölze *et al*. (2000), in their review of European farming systems, saw trends toward lower CO_2 emissions in organic agriculture but were not able to conclude that overall CO_2 emissions are lower per unit of product in organic systems compared to the conventional ones. The authors reported that the 30% higher yields in conventional intensive farming in Europe can compensate for the lower CO_2 emissions per unit of products in organic agriculture.

Haas *et al*. (2001) conducted a Life Cycle Assessment of the environmental impacts of 18 grassland farms in three different farming intensities (intensive, extensified, and organic) in southern Germany. They found that extensified and organic farms reduce energy consumption and Global Warming Potential (GWP). The authors found that the area-related GWP decreases for intensive (9.4 t CO_2 eq. ha^{-1}), extensified (7.0 t CO_2 eq. ha^{-1}) and organic farms (6.3 t CO_2 ha^{-1}), accordingly. With regards to product-related energy use, extensified farms (1.0 t CO_2 eq. ha^{-1}) cause the lowest GWP, whereas intensified and organic farms (1.3 t CO_2 eq. ha^{-1}) produce the same emissions. Lower CO_2^- and N_2O^-emissions of organic farms are compensated by a higher emission of CH_4 per unit of produced milk, because of lower milk yields.

Comparing the performances of single crops can produce very different results from those obtained when comparing the whole cropping system within which that specific crop is found. Küstermann *et al*. (2008), for instance, report that GHGs per ha for winter wheat are comparable between organic and conventional system. On a harvested biomass basis, lower yields in organic farming involved higher emissions (496 kg CO_2 eq. Mg^{-1} for the organic system and 355 kg CO_2 eq. Mg^{-1} for the conventional), when all products relating to the whole crop rotation are considered, organic management is shown to result in lower emission (263 kg CO_2 eq. Mg^{-1}, for the organic system against 376 kg CO_2 eq. Mg^{-1} for the conventional system) (Table 4).

Modeling of a transition to organic production in Canada, Pelletier *et al*. (2008) found that a total transition of Canadian canola, corn, soybean and wheat production to organic management may reduce the overall national energy consumption by 0.8%, GHGs emissions by 0.6%, and acidifying emissions (from N and S compounds) by 1%. The authors argue that although organic farming systems have a slightly higher fuel-related energy consumption, still their average total energy demand has been estimated at about 40% that of conventional management, mainly due to the use of synthetic fertilizer and pesticide (quite costly in terms of energy demand) in conventional systems. Such calculations, however, do not account for organic compost shipments over long distance.

Wood *et al.* (2006) carried out a comprehensive environmental impacts analysis of Australian agriculture, and argue that organic production has smaller indirect impacts than conventional production, and that a transition to organic farming could be a viable way of reducing energy use and GHG emissions, while maintaining employment and economic benefits. In their review, Lynch *et al*. (2011) fond that organic systems has gnerally lower GHGs emission per ha but the results are variable on a per unit of product basis.

C. Integrating Animal Husbandry

In organic farming, animal husbandry is carried out taking into account ethical concerns regarding the well being of the animals, and therefore, amongst other practices, it promotes natural behavior of cows by having them spend most of the grazing period outdoors, it limits the use of drugs and endorses the use of feed coming from crops where the use of synthetic fertilizers and pesticides is forbidden (Lund, 2006). This translates to better consumer health, having meat without an extra supply of (synthetic) hormones and traces of antibiotics.

According to some authors (Subak, 1999; Cederberg and Stadig, 2003; Koneswaran and Nierenberg, 2008a, 2008b)

TABLE 4
CO_2 emissions for some productions (data from Küstermann *et al.*, 2008).

	GHGs emission per ha (kg CO_2 eq. ha^{-1})			GHGs emission per production unit (kg CO_2 eq. t^{-1})		
Study	Conv.	Organic	Org. as % of conv.	Conv.	Organic	Org. as % of conv.
Winter wheat	2,333	1,669	71	355	496	140
Similar crop rotation	2,717	887	32	376	263	70

organic animal husbandry has the potential to reduce GHG emissions and sequester carbon through better pasture management. Raising cattle for beef organically on grass, in contrast to fattening confined cattle on concentrated feed, may emit 40% less GHGs and consume 85% less energy than conventionally produced beef. According to Williams *et al*. (2006), most organic animal production reduces primary energy use by 15% to 40%, with the exception of organic poultry meat and egg production, which increase energy use by 30% and 15% respectively.

How to develop appropriate analytical methods to assess the sustainability of organic meat and milk production is, however, still work in progress and a matter of debate (e.g., De Boer, 2003; Avery and Avery, 2008; Koneswaran and Nierenberg, 2008a; 2008b; Müller-Lindenlauf *et al*., 2010).

A study of German dairies by Haas *et al*. (2001) reports an energy use per unit of milk for organic agriculture that is less than half of that of conventional farming, and less than one-third per unit of land. For instance, De Boer (2003), argued that at present we cannot directly compare results of different LCA studies. The author noted that, for example, absolute GWP differs largely among studies because of differences in allocation or normative values used with respect to CH_4 and N_2O emission. Lacking a standardized protocol for LCA, De Boer (2003, p. 76) stated that "conventional and organic production systems can be compared only within a case study." Avery and Avery (2008) of the Huston Institute (a think tank based in Washington D.C.), challenged the data by Koneswaran and Nierenberg (2008a), whose figures indicated organic animal production systems performing better than conventional, claiming that the authors were comparing highly different environmental and cultural contexts (Sweden and Japan), and citing different studies to support different conclusion. Koneswaran and Nierenberg (2008a; 2008b), on the other hand, replied that the LCA cited by Avery and Avery (2008) are still misleading and, in some cases, wrongly quoted. Further to the LCA issue, De Boer (2003), argued also that experimental farms, from which comparison between organic and conventional animal production are made, do not necessarily represent corresponding production systems. Müller-Lindenlauf *et al*. (2010), called for the adoption of a more complex approach, arguing that focussing only on the classical environmental impact categories (e.g. energy efficiency, GWP) may lead to different results than a system approach that includes a broader range of relevant impacts and ecological benefits. However, there were slightly higher methane emissions per unit of organically produced milk, and the authors estimated that the final GWP of the two farming systems was similar (Tables 5a and 5b). Most LCA undertaken thus far report that organic management results in a bit less or equal footprints as compared to conventional. While outcomes rate organic management positively on a per hectare basis, performance per unit of production is less positive as organic management tends to yield less than conventional.

A German study based on a multicriterial assessment of milk production of organic and conventional farms (Müller-Lindenlauf *et al.*, 2010), concludes that organic farming tends to have less negative environmental effects than conventional farming. Results are, however, not neat. The authors found that intensive farm types tend to be advantageous in global categories such as climate impact and land demand. On the other hand, low-input farm types have significant advantages with regards to ammonia emissions, animal welfare and milk quality. The authors argue that carrying on an environmental impact assessment analyzing only a few indicators, e.g., GHGs emission and energy consumption, leads to different conclusions than an overall analysis taking into account a large number of regional and local factors. When considering land demand Müller-Lindenlauf *et al.* (2010) report that arable land demand (ha/1000 kg milk) was 0.07 for organic grasslands vs. 0.1 for conventional grasslands, and 0.03 for organic mix farm vs. 0.1 for conventional mix farm. That means that organic milk production was 3 to 10 times less dependent on arable land. Even if organic management resulted slightly higher on the overall land

TABLE 5a
Energy use and carbon emission in milk production in organic and conventional systems.

	Energy Consumption (GJ ha^{-1})			Energy Consumption (GJ t^{-1})		
Study	Conv.	Organic	Org. as % of conv.	Conv.	Organic	Org. as % of conv.
Cederberg and Mattsson (1998)	22.2	17.2	77	2.85	2.41	85
Refsgaard *et al.* (1998)	–	–	–	3.34	2.16/2.88	75/87
Cederberg and Mattsson (1998) in Haas *et al.* (2001)	–	–	–	2.85	2.4	92
Haas *et al.* (1995) in Haas *et al.* (2001)	19.4	6.8	35	–	–	–
Haas *et al.* (2001)	19.1	5.9	31	2.7	1.2	46
Thomassen *et al.* (2008)*				4.4	2.17	51
Müller-Lindenlauf *et al.* (2010) – Grassland	–	–	–	1.52	1.2	79
Müller-Lindenlauf *et al.* (2010) – Mix farm	–	–	–	1.17	1.32	113

(*) including indirect costs.

TABLE 5b
Energy use and carbon emission in milk production in organic and conventional systems.

	CO_2 Emission (kg CO_2 ha^{-1})			CO_2 Emission per Production Unit (kg CO_2 t^{-1})		
Study	Conv.	Organic	Org. as % of conv.	Conv.	Organic	Org. as % of conv.
Haas *et al.* (2001)	9,400	6,300	67	1,280[a]	428[a]	33
Haas *et al.* (2001)	–	–	–	1,300[b]	1,300[b]	0
Thomassen *et al.* (2008)*	–	–	–	1,400	1,500	107
Müller-Lindenlauf *et al.* (2010)–Grassland	–	–	–	1,036	1,172	113
Müller-Lindenlauf *et al.* (2010)–Mix farm	–	–	–	917	1,082	118

[a]considering only CO_2 emission; [b]summing up CH_4 and N_2O emissions as CO_2 equivalents, the CH_4 and N_2O emissions are comparably low, but due to the high Global Warming Potential (GWP) of these trace gases their climate relevance is much higher.
(*) including indirect costs.

demand (0.31 and 0.28 for organic vs. 0.27 and 0.22 for conventional), still the impact of organic farming on soil (e.g., soil loss, SOM, biodiversity) can be considered lower than that of conventional farming. Again, neither chemical residues in milk nor pesticide use in crops production were taken into consideration as sustainability indicators (and in some contexts pesticide use is indeed a cause of concern). The points raised should not be taken as criticism, as the work just described can be considered a nice and welcomed attempt to adopt a multicriterial approach in order to account for key indicators in a comprehensive farming system analysis. Our aim is to illustrate the complex nature of farming system analysis when attempting a comparison between different systems and the assessment of what is "the best."

In a review comparing milk production performance of organic and conventional systems, De Boer (2003) claims that few exact figures are available, especially on the amount of NO_2 and CH_4 emitted from dairy cattle production, and concludes that, firstly, the potential environmental impact of conventional and organic milk production is based largely on comparison of experimental farms, which do not necessarily represent the corresponding production systems Secondly, he suggests that different indicators provide different levels of performance; for instance, CH_4 emission appears higher in organic systems, while eutrophication potential per tonne of milk and per ha appears lower for organic milk production than for conventional. Thirdly the author argues that organic milk production potentially reduces leaching of NO_3^- and PO_4^-, due to lower fertilizer application rates.

VI. CONSTRAINTS TO THE ADOPTION OF ORGANIC AGRICULTURE

A. Feasibility

The benefits associated with the adoption of organic farming practices have been questioned by many authors to different degrees. Some authors claim that organic farming is an ideology rather than a scientific approach to agriculture (e.g., Kirchmann and Thorvaldsson, 2000; Rigby and Càceres, 2001; Trewavas, 2001, 2004; Edwards-Jones and Howells, 2001; De Gregori, 2003). Others express a milder form of criticism based on the concern that not all organic agriculture strategies can be applied globally and without many local adjustments, and because of this lack of coherence, they suggest that this approach may actually lead to a worsening of agricultural problems (e.g., Tilman *et al.*, 2002; Elliot and Mumford, 2002; Wu and Sardo, 2010).

Some authors (e.g., Elliot and Mumford, 2002) suggest the adoption of integrated farming, rather than upholding solely organic practices, which they find more harmful than conventional farming, for instance in the case of pest control technologies.

B. Labor Productivity

When assessing the socioeconomic sustainability of farming enterprises, labor productivity is a key indicator. Organic farms, although performing better in terms of energy efficiency, generally require more labor than conventional ones, ranging from about 10% up to 90% (in general about 20%), with lower values for organic arable and mixed farms and higher labor inputs for horticultural farms (Lockeretz *et al.*, 1981; Pimentel *et al.*, 1983; 2005; FAO, 2002; Foster *et al.*, 2006).

Case studies in Europe for organic dairy farms report a comparable high labor input (FAO, 2002). Little data exists for pig and poultry farms. In some long term trials, productivity per hectare and hour of work for organic and conventional crops (corn and soybean) were comparable (Pimentel *et al.*, 2005; Pimentel, 2006).

In order to gain insight into the sustainability of a farming system, different perspectives such as land use, working time and energy use should be employed at the same time (Giampietro, 2004; Gomiero *et al.*, 2006). Data on energy efficiency cannot be detached from the "metabolism" of the social system where agriculture is performed. High energy efficiency may imply low total energy output that, for a large society with limited land, may not be a sustainable option, menacing food supply for urban populations. With the current emphasis on promoting a green economy and paying farmers for environmental services, organic agriculture offers great potential to generate green jobs and revitalize rural areas. We warn, however, about looking at organic agriculture as a mean to produce biofuels (Giampietro and Ulgiati, 2005; Pimentel and Patzek, 2005; Giampietro and Mayumi, 2009; Gomiero *et al*., 2010).

C. Economic Performance

Comparing organic and conventional system is still not an easy task because authors often adopt quite different methodologies, and different geographical areas (e.g., developed and developing countries) have distinctive characteristics that should be properly taken into consideration (Nemes, 2009). Although yields in organic systems tend to be lower, input costs are usually lower. A number of studies report no major revenue difference for organic farming compared to conventional (e.g., Drinkwater *et al*., 1998; Delate *et al*. 2003; Pacini *et al.,* 2003; Mahoney *et al*., 2004; Pimentel *et al.,* 2005, for a comprehensive review of the topic see Nemes, 2009).

According to the U.S. Department of Agriculture (USDA, 2010a; Bowman, 2010), data from the organic farming census reveal that the 14,540 organic farms included in the census had an estimated average net income (total sales less expenses) of $20,249 per farm per year, a figure higher than the figure in which all farm types were included.

This has been reported also in some broad research conducted in developing countries. For instance, Eyhorn *et al*. (2007) found that in India the average gross margins from organic cotton fields were 30–40% higher than in conventional fields, due to 10–20% lower total production costs and a 20% organic price premium. Authors argue that although the crops grown in rotation with cotton were sold without premium, organic farms achieved all the same 10–20% higher incomes from agricultural activity.

Other studies, however, indicate that the impact of organic price premiums is large, and sometimes needed to match conventionally generated income and compensate for lower yields (e.g., Reganold *et al*., 2001; Pacini *et al.,* 2003; Chavas *et al*., 2009; Nemes, 2009). Recent analysis for southern Wisconsin (USA) by Chavas *et al.* (2009) shows that, under the market scenarios that prevailed between 1993 and 2006, intensive rotational grazing and organic grain and forage systems were the most profitable systems. On, highly productive land organically grown corn resulted more profitable than continuous corn cropping. Once the premium was taken into account, organic farming resulted more profitable in all systems. Results for Low External Input (LEI) agriculture in the United States (Liebman *et al*., 2008) shows that corn and soybean yields in LEI systems can be sustained at levels that match or exceed levels obtained from conventional systems. Scenario analysis by Lohr and Park (2007) indicates that economic gains will be realized as farm size increases, creating pressure on organic farmers to expand operations. Protecting small organic farms is likely to become a policy issue in the near future.

D. Environmental Services of Organic Agriculture

Economic benefits from agriculture management cannot be limited to yield or commodities production, or account only for farm investment and revenue. For instance, issues such as energy efficiency and GHGs emissions, preserving water supply, biodiversity and landscape preservation and reduction in the use of agrochemicals are usually not assessed when conducting farming cost-benefit analyses. Still they play a key role for the long term sustainability of our support system and our environment, even if they have to be addressed on a broader spatial and temporal scale (Paoletti and Pimentel, 1992; Pimentel *et al.*, 1997; Tilman *et al*., 2001, 2002; Pretty *et al.*, 2003; FAO, 2004; Foley *et al.*, 2005; Millennium Ecosystem Assessment, 2005a; 2005b; Molden, 2007; Bosshard *et al*., 2009; Vitousek, *et al*., 2009).

It should be noted that organic agriculture provides many beneficial "by-products" both for the environment (e.g., conservation of soil fertility, CO_2 storage, fossil fuel reduction, preserving biodiversity) and for people (e.g., eliminating the use of agrochemicals such as synthetic fertilizers and pesticides, preserving landscape). We wish to stress that preserving or increasing soil organic matter content has to do not only with a farm long-term sustainability (and benefit), but, and maybe most importantly, with preserving a country's long term food security, guaranteeing that it can overcome and recover from possible future climate extremes.

In this sense it is important to get a deeper understanding of the nature of agroecosystems: they are embedded in complex ecological networks, characterized by nonlinearity and stochasticity. Theoretical and empirical research reveals that ecological systems persist and generate ecosystem services as a result of complex interacting components (Ehrlich and Ehrlich, 1981; Paoletti and Pimentel, 1992; Cliff, 1997; Pimentel *et al*., 1997; 2006; Loreau *et al*., 2002; Luck *et al*., 2009; Vandermeer *et al*., 2010). Benefits from insect services in the United States, for instance, are valued at $57 billion per year (Losey and Vaughan, 2006). But insect do not live in a vacuum, they are constrained by the environment-landscape characteristics. Eventually, benefits provided by insects depend on how we decide to manage the environment in which they may find their living from which they depend on. So, in order to fully benefit from ecosystems environmental services, we should manage our environmental at a broader scale than that of the single farm.

At the same time, economic analysis should take full account ("internalization") of the economic impact of conventional agriculture, addressing the issue of its long term sustainability (Pimentel *at al.*, 1995, 1997; Pretty *et al*., 2000, 2003; Buttel, 2003).

E. Organic Farming and Food Security

According to some authors organic agriculture can be a promising approach to sustain food security while decreasing the environmental impact of agriculture, especially in some developing countries (Pretty and Hine, 2001; Altieri, 2002; FAO, 2002, 2008; Pretty, 2002; van Veluw, 2006; Niggli *et al*., 2007, 2008; El-Hage Scialabba, 2007; Badgley *et al*., 2008; El-Hage Scialabba and Müller-Lindenlauf, 2010). In low input systems, and especially in arid and semi-arid areas where most of the food-insecure people live, organic systems are reported to greatly improve yields (Pretty and Hine, 2001; Pretty, 2002). Although for perennial cropping, such as coffee or banana, significant yield reductions are reported, under appropriate agroforestry system, the lower yields for the main crop are compensated by producing other foodstuff and goods (El-Hage Scialabba and Müller-Lindenlauf, 2010).

Some authors (e.g., Pretty and Hine, 2001; FAO, 2002, 2008; Halberg *et al*., 2006; Badgley and Perfecto, 2007; Badgley *et al*., 2007; El-Hage Scialabba, 2007; Niggli *et al.*, 2007, 2008) argue that organic agriculture could benefit developing countries because organic practices contribute considerably to increasing soil stability and resilience, an important factor in food supply stability, and also save water, another critical resource in many areas. The authors claim that the productivity of organic compared to conventional farming depends strongly on soil and climate conditions as well as on choice of crops being compared, and under less favorable soil conditions, organically managed crop yields equal those from conventional agriculture. Recent models of a hypothetical global food supply grown organically (Badgley, *et al*., 2007; Halberg, *et al*., 2006) indicates that organic agriculture could produce enough food on a global *per capita* basis for the current world population.

In their review, Badgley *et al*. (2007) compared yields of organic versus conventional or low-intensive food production for a global dataset of 293 examples and estimated the average yield ratio (organic vs. nonorganic) of different food categories for the developed and the developing world, and found that for most food categories the average yield ratio was slightly <1.0 for studies in the developed world and >1.0 for studies in the developing world. The authors found also that in developed countries average yield losses under organic management ranged from 0 to 20% (Badgley *et al*., 2007). Pretty and Hine (2001) surveyed 208 projects in developing tropical countries in which contemporary organic practices were introduced, and found that average yield increased by 5–10% in irrigated crops, and by 50–100% in rain-fed crops. Data from Pretty and Hine (2001) have been challenged by some authors (e.g., McDonald *et al*., 2005; Cassman, 2007; Hudson Institute, 2007; Hendrix, 2007), who dispute the correctness of both the accounting (they hold that, in some of the cases reported, pesticides may have been used) and comparative methods employed. Cassman (2007) criticizes both the findings and the approach to the problem of food security adopted by the supporters of organic farming, and argues that what is needed to produce 60% more food by 2050 to meet demand from growth in both population and income is ecological intensification of crop production systems rather than relying on the organic farming approach.

F. "Food Miles" Analysis

Most energy in the food system is post-production. Food processing, distribution, wholesale and retail can amount to two thirds of total energy expenditure (Pimentel and Pimentel, 2008; Smil, 2008). It has been estimated that in the United States, on-farm production amounts to approximately 20% of the total food system energy, with about 40% of this amount going into making chemical fertilizers and pesticides (Keoleian and Keoleian, 2000).

National and international trade results in increasing "food miles" (the distance that food travels from the field to the grocery store), which may lead to increasing the overall energy consumption and CO_2 emissions associated with a given product (Pimentel *et al*., 1973; Steinhart and Steinhart, 1974; DEFRA, 2005; Pretty *et al*., 2005; Schlich and Fleissner, 2005; Foster *et al*., 2006, Pimentel and Pimentel, 2008). To avoid such a problem, environmental groups and organic associations are advising consumers to consume locally produced food as part of environmentally friendly eating habits. This, however, may limit export of organic products from developing countries to western markets, reducing the income for poor farmers and the adoption of sustainable farming practices.

Some authors challenge such a claim as too simplistic a view, and make the point that agricultural products imported from far away may cause lower environmental impact than locally produced products, for example when the latter have to be kept stored in fridges for several months (e.g., fruits) (Wells, 2001; Saunders *et al*., 2006; Williams, 2007; El-Hage Scialabba and Müller-Lindenlauf, 2010). Saunders *et al*. (2006), for instance, report that in the case of dairy and sheep meat production, New Zealand is by far more energy efficient than the UK even including transport costs, twice as efficient in the case of dairy, and four times as efficient in case of sheep meat. Wells (2001) found that New Zealand dairy production was on average less energy intensive than in North America or Europe even though on-farm primary energy input had doubled in 20 years and energy ratio (outputs vs. inputs) had increased by 10%. Williams (2007) reports that Dutch CO_2 emissions for rose cultivation were about 6 times larger than producing them in Kenya and delivering the product to Europe.

VII. CONCLUSIONS

In the last century, intensive farming has successfully achieved high crop yields. On the other hand this came with a cost on the environmental side because of the high intensity of energy use (agrochemical, machinery, water pumping etc) and GHGs emissions, water consumption and the large use of agrochemicals, which, other than being costly in energy terms, have also detrimental effects on the health of organisms, humans included.

When comparing the performances of organic and conventional agricultural practices it has been shown that organic generally performs better or much better than conventional for a wide range of key indicators (Table 1). Such improved performances have been summarised in previous reviews such as Stölze *et al*. (2000), Stockdale *et al*. (2001); FAO (2002), Lotter *et al*. (2003), Shepherd *et al*. (2003), Kasperczyk and Knickel (2006), Niggli *et al*. (2007), Gomiero *et al*. (2008), as well as proven in long term monitoring trials (e.g., Reganold *et al*., 1987; Matson *et al*., 1997; Paoletti *et al*., 1998, Drinkwater *et al*., 1998; Mäder *et al.*, 2002a, 2002b; Pacini *et al.*, 2003; Pimentel *et al*., 2005; Badgley *et al*., 2007). However, it has to be pointed out that in some cases performance can vary according to specific crop species and crop patterns and in relation to the environmental context where agricultural activity is performed.

In the following section we provide some more detailed comments on the performances of organic agriculture on some key environmental issues. We will deal in particular with soil, biodiversity, energy and GHG emission.

Table 6 is an attempt to further develop the qualitative review efforts made by Stölze *et al*. (2000) and Lotter, (2003). Assessments are only indicative and no claim is made to provide weighted qualitative values of farming performance.

As pointed out by Pacini *et al.* (2003), the fact that in most cases organic farming systems perform better environmentally than conventional or integrated farming system, does not directly imply that they are sustainable when compared to the intrinsic carrying capacity and resilience of a given ecosystem. Comparison between organic and conventional (or other) farming systems is much needed, but to assess sustainability in the long term, proper comparisons have to be made taking into account the local (and global) carrying capacity of the agroecosystem.

To date, many studies prove organic farming to perform better in improving soil quality with respect to both biophysical and ecological properties. Organic farming prevents soil erosion, increases SOM (promoting soil biodiversity and soil health) and can reduce N leaching. Increases in SOM following the transition to organic management occur slowly. This has to be of concern when assessing the performances of farming systems under different management practices. Soil under organic management greatly increases their water holding capability and under drought conditions crops in organically managed systems produce higher yields than comparable crops managed conventionally. Adaptive measures to cope with climate change should treasure knowledge gained from organic farming. Local characteristics deserve attention, as agricultural practices should not be adopted blindly, but with much concern for specific local features. What may fit a given area may not be practicable with the same results in another (e.g., plain vs. sloping land).

Agriculture intensification results also in a dramatic simplification of landscape composition and in a sharp decline of biodiversity. This affects the functioning of natural pest control, as natural habitats provide shelter for a broad spectrum of natural species that operate as pest-control in agriculture crops. Organic farming tends to rely on a higher number of crops, compared to conventional, because of the very nature of the management system, involving rotation, cover crops, intercropping and set

TABLE 6

Overall qualitative assessment of organic farming systems relative to conventional farming*. (Organic farming performs: ++ much better, + better, 0 the same, − worse, – much worse).

Indicator − Performance	Qualitative Assessment				
	++	+	0	−	−−
Agronomic					
Productivity as yield per ha		+	0	−	−−
Productivity as yield per hr				−	−−
Biodiversity					
Crop diversity	++	+	0		
Floral diversity	++	+			
Aboveground faunal diversity (invertebrate and vertebrate)	++	+			
Habitat diversity	++	+	0		
Effect on pest control and pollinators	++	+			
Soil biophysical characteristics					
Organic matter	++	+	0		
Structure	++	+	0		
Soil biology	++	+	0	−	
Microbial biomass	++	+			
Microbial activity	++	+			
Mycorrhizae	++				
Biodiversity	++	+			
Effect on pest control	++	+	0		
Ground and surface water					
Nitrate leaching	++	+	0	−	
Pesticides	++				
Greenhouse emissions (including CO_2, CH_4, N_2O, NH_3)					
GHGs per ha	++	+			
GHGs per ton biomass		+	0	−	
Farm input and output					
Nutrient use		+			
Water use		+	0		
Energy use per ha	++	+			
Energy use per ton biomass		+	0	−	
Animal welfare and health					
Husbandry		+			
Health	++	+			
Quality of product food					
Pesticides residues	++	+			
Nitrate		+	0	−	
Mycotoxins		+	0	−	
Heavy metals		+	0	−	
Antibiotics	++				

(*): the list of indicators has been expanded from Stölze *et al.* (2000) and Lotter (2003), and quality assessment modified according to the data found by the present review.

aside. A more complex crop pattern offers more chances for "wild biodiversity" to thrive.

According to the studies reviewed, organic farming provides greater potential for biodiversity than its conventional counterpart, as a result of greater habitat variability and more wildlife-friendly management practices, and, to a lesser extent, due to the exclusion of pesticides. This greater potential is more readily observed primarily for wild plants, but also for their hosts. Indeed, an increasing body of evidence indicates that landscape heterogeneity is a key factor in promoting biodiversity in the agricultural landscape.

The effect of organic agriculture on promoting biodiversity may also vary according to the specific taxa and the surrounding conditions where a farm operates. Research indicates the need for long term, system-level studies of the biodiversity response to organic farming. It is noted that such benefits may be achieved also by conventional agriculture when carefully managed.

Promoting heterogeneity widely across agricultural systems should be a universal management objective. Large areas converted to organic management may generate positive feedbacks on biodiversity because of scale effect (the larger the areas the greater the benefits), suggesting that measures to preserve and enhance biodiversity in agroecosystems should be both landscape- and farm-specific.

Energy efficiency and GHG emission reduction are certainly important indicators of farming system performances. Organic farming has been shown to providing a better of energy input/output ratio. The main reasons for higher efficiency are lack of input of synthetic agrochemical (e.g., fertilizers, pesticides) and lower use of highly energy-consumptive foodstuffs (concentrates). However, due to the general lower yield of crops under organic farming, when calculating energy input in terms of unit of physical output, the advantage to organic systems was generally not as significant. Organic agriculture may represent a means for reducing GHG emission, both because of its lower energy consumption and of its soil management practices that help to reduce GHG emission and absorb carbon in soil. Conversion to organic agriculture, however, only represents a temporary solution to the problem of carbon abatement because the possibility to stock carbon in the soil has limits. Long-term solutions concerning CO_2 and GHG emission abatement should rely on a more general change of our development path, for instance in containing energy consumption in general. Other beneficial "by-products" provided by organic farming both for the environment (e.g., reducing pollution, fostering biodiversity) and for human health (e.g., exposure to harmful chemicals), also should be properly accounted for.

Carrying out extensive long-term trials for diverse crops in diverse areas would be of fundamental importance in order to understand the potential of organic farming as well as to improve farming techniques in general. Investing in organic farming research will help to gain knowledge and experience about best practices for agroecosystem management.

According to Niggli *et al.* (2008), there are three strategic research priorities for agricultural and food research:

- Viable concepts for the empowerment of rural economies in a regional and global context
- Securing food and ecosystems by means of eco-functional agricultural intensification
- High quality foods—a basis for healthy diets and a key for improving our quality of life and health.

Researching organic food and farming systems can contribute greatly towards the overall sustainability of agriculture and food production by providing a holistic analysis of system factor interactions and trade-offs in order to meet new challenges.

We would like to conclude by reminding each of us that we all depend inescapably on agriculture for our life. We feel that maybe there has been too much focus on agriculture as a mere economic activity, forgetting that, differently from all other economic activities, this is the only one that we cannot afford to dismiss or allow ourselves to lose.

ACKNOWLEDGMENTS

We wish to thank Nadia El-Hage Scialabba at Natural Resources Management and Environment Department at FAO, Rome, for her valuable comments, which helped to improve the manuscript. We also wish to thank Dr. Lucio Marcello, Glasgow Biomedical Research Centre, University of Glasgow, for helping to edit this manuscript. Part of this work has been carried out within the EU FP7 research project "Indicators for biodiversity in organic and low-input farming systems" (BIO-BIO KBBE-2008-1-2-01). The European Union or the European Union Commission cannot be held responsible for results and opinions quoted in the text.

REFERENCES

Alyokhin, A., Porter, G., Groden, E., and Drummond, F. 2005. Colorado potato beetle response to soil amendments: A case in support of the mineral balance hypothesis? *Agric. Ecosys. & Environ.* **109:** 234–244.

Altieri, M. 1987. *Agroecology: The Science of Sustainable Agriculture*. Westview Press, Boulder, NY, USA.

Altieri, M. 2002. Agroecology: The science of natural resource management for poor farmers in marginal environments. *Agric., Ecosys. and Environ.* **93:** 1–24.

Altieri, M., and Nicholls, C. I. 2004. *Biodiversity and Pest Management in Agroecosystems.* (2nd ed.) CRC Press, Boca Raton, FL, USA.

Anderson, K., Cockburn, J., and Martin, W. 2010. *Agricultural Price Distortions, Inequality, and Poverty*. World Bank Publications, Washington D.C.

Avery, A., and Avery, D. 2008. Beef production and greenhouse gas emissions. *Environmental Health Perspectives* **116:** 373–374.

Badgley, C., and Perfecto, I. 2007.Can organic agriculture feed the world? *Renewable Agriculture and Food Systems* **22:** 80–85.

Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, J. M., Avilés-Vázquez, K., Samulon, A., and Perfecto, I. 2007. Organic agriculture and the global food supply. *Renewable Agriculture and Food Systems* **22:** 86–108.

Bahlai, C. A., Xue, Y., McCreary, C. M., Schaafsma, A. W., and Hallett, R. H. 2011. Choosing Organic Pesticides over Synthetic Pesticides May Not Effectively Mitigate Environmental Risk in Soybeans. *PlosOne* **5**(6): e11250.

Balfour, E. 1977. Towards a Sustainable Agriculture: The Living Soil. IFOAM conference, Switzerland, 1977. http://www.soilandhealth.org/01aglibrary/010116balfourspeech.html Accessed on 20 November 20009.

Barberi, P. 2002. Weed management in organic agriculture: Are we addressing the right issues? *Weed Research* **42:** 177–193.

Barbosa, P. 2003. *Conservation Biological Control*. Academic Press, San Diego, USA.

Bengtsson, J., Ahnstrom, J., and Weibull, A-C. 2005. The effects of organic agriculture on biodiversity and abundance: A meta-analysis. *J. Appl. Ecol.* **42:** 261–269.

Benton, T. G., Vickery, J. A., and Wilson, J. D. 2003. Farmland biodiversity: Is habitat heterogeneity the key? *Trends Ecol. Evol.* **18**:182–188.

Bianchi, F.J.J.A., Booij, C. J. H., and Tscharntke, T. 2006. Sustainable pest regulation in agricultural landscapes: A review on landscape composition, biodiversity and natural pest control. *Proc. R. Soc. B* **273:** 1715–1727.

Birkhofer, K., Bezemer, T. M., et al. 2008. Long-term organic farming fosters below and aboveground biota: Implications for soil quality, biological control and productivity. *Soil Biology & Biochemistry* **40:** 2297–2308.

Bosshard, A., Reinhard, B. R., and Taylor, S. (Eds.). 2009. *IFOAM Guide to Biodiversity and Landscape Quality in Organic Agriculture.* IFOAM http://www.ifoam.org/growing_organic/7_training/training_pdf/Biodiversity Book–2009-07-15-AZ-Teaser.pdf Accessed on 20 August 2009.

Bowman, G. 2010. USDA census shows profitability of organic farming. Rodale Institute. http://www.rodaleinstitute.org/20100319/nf_USDA-census-shows-profitability-of-organic-farming Accessed on 20 July 2010.

Briar, S. S., Grewal, P. S., Somasekhar, N., Stinner, D., and Miller, S. A. 2007. Soil nematode community, organic matter, microbial biomass and nitrogen dynamics in field plots transitioning from conventional to organic management. *Appl. Soil. Ecol.* **37:** 256–266.

Brittain, C., Bommarco, R., Vighi, M., Settele, J., and Potts, S. G. 2010. Organic farming in isolated landscapes does not benefit flower-visiting insects and pollination. *Biological Conservation* **143:** 1860–1867.

Büchs, W. (Ed.) 2003. Biotic indicators for biodiversity and sustainable agriculture. *Agric. Ecosys. & Environ*. **98,** Special Issue. Elsevier Amsterdam.

Butler, S. J., Vickery, J. A., and Norris, K. 2007. Farmland biodiversity and the footprint of agriculture. *Science* **315:** 381–384.

Buttel, F. H. 2003. Internalizing the societal costs of agricultural production. *Plant Physiol.* **133:** 1656–1665.

Caporali, F., Mancinelli, R., and Campiglia, E. 2003. Indicators of cropping system diversity in organic and conventional farms in Central Italy. *Int. J. Agric. Sust*. **1:** 67–72.

Cassman, K. 2007. Editorial response by Kenneth Cassman: Can organic agriculture feed the world-science to the rescue? *Renew. Agric. and Food Syst.* **22:** 83–84.

Cavigelli, M. A., Teasdale, J. R., and Conklin, A. E. 2007. Long-term agronomic performance of organic and conventional field crops in the Mid-Atlantic Region. *Agronomy J.* **100:** 785–794.

Cederberg, C., and Stadig, M. 2003. System expansion and allocation in life cycle assessment of milk and beef production. *Int. J. Life Cycle Assess*. **8:** 350–356.

Chandler, S., and Dunwell, J. M. 2008. Gene flow, risk assessment and the environmental release of transgenic plants. *Critical Reviews in Plant Sciences* **27:** 25–49.

Chavas, J-P, Posner, J. L., and Hedtck, J. L. 2009.Organic and conventional production systems in the wisconsin integrated cropping systems trial: II. Economic and risk analysis 1993–2006. *Agron. J*. **101**:288–295.

Chivian, E., and Bernstein, A. (Eds). 2008. *Sustaining Life: How Human Health Depends on Biodiversity.* Oxford University Press, New York.

Clark, M.S., Horwath, W. R., Shennan, C., and Scow, K. M. 1998. Changes in soil chemical properties resulting from organic and low-input farming practices. *Agronomy J.* **90:** 662–671.

Clark, M. S., Horwath,W. R., Shennan,C., Scow, K. M., Lantni, W.T., and Ferris, H. 1999. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. *Agric. Ecosys & Environ.* **73:** 257–270.

Clark, S., Szlavecz, K., Cavigelli, M. A., and Purringto, F. 2006. Ground Beetle (Coleoptera: Carabidae) assemblages in organic, no-till, and chisel-till cropping systems in Maryland. *Environmental Entomology* **35:** 1304–1312.

Cliff., B. 1997. Economic and environmental benefits of biodiversity. *BioScience* **47:** 747–757.

Clough, Y., Kruess, A., and Tscharntke, T. 2007a. Local and landscape factors in differently managed arable fields affect the insect herbivore community of a non-crop plant species. *J. Appl. Ecol.* **44:** 22–28.

Clough, Y., Holzschuh, A., Gabriel, D., Purtauf, T., Kleijn, D., Kruess, A., Steffan-Dewenter, I., and Tscharntke, T. 2007b. Alpha and beta diversity of arthropods and plants in organically and conventionally managed wheat fields. *J. Appl. Ecol.* **44:** 804–812.

Codex Alimentarius. 2004. G*uidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods* (GL 32 – 1999, Rev. 1 – 2001). Internet http://www.codexalimentarius.net/web/standard_list.do?lang=en. Accessed on November 24, 2007.

Conford, P. 2001. *The Origins of the Organic Movement*. Floris Books, Glasgow, UK.

Cormack, W. F. 2000. *Energy Use in Organic Farming Systems*. Final report for project OF0182 for the Department for Environment, Food and Rural Affairs. http://orgprints.org/8169/01/OF0182 181 FRP.pdf. Accessed on December 12, 2008 from

Courville, S. 2006. Organic standards and certification. **In:** *Organic Agriculture. A Global Perspective.* pp. 201–220. Kristiansen, P., Taji, A., and Reganold, J., Eds., CSIRO Publishing, Collingwood, Australia.

Crowder, D. W., Northfield, T. D., Strand, M. R., and Snyder, W. E. 2010. Organic agriculture promotes evenness and natural pest control. *Nature* **466:** 109–112.

Czech, B., Krausman, P. R., and Devers, P. K. 2000. Economic associations among causes of species endangerment in the United States. *BioScience* **50:** 593–601.

Dalgaard, T., Halberg, N., and Porter, J. R. 2001. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agric., Ecosys. & Environ.* **87:** 51–65.

De Boer, I.J.M. 2003. Environmental impact assessment of conventional and organic milk production. *Livestock Production Science* **80:** 69–77.

DEFRA (Department for Environment Food and Rural Affairs – UK). 2005. The validity of food miles as an indicator of sustainable development. Report number ED50254. Retrieved September 16 2007 from http://statistics.defra.gov.uk/esg/reports/foodmiles/default.asp.

De Gregori, T. R. 2003. *Origins of the Organic Agriculture Debate*. Wiley-Blackwell, Oxford.

Delate, K., and Cambardella, C. A. 2004. Agroecosystem performance during transition to certified organic grain production. *Agron. J.* **96:** 1288–1298.

Delate, K., Duffy, M., Chase, C., Holste, A., Friedrich, H., and Wantate, N. 2003. An economic comparison of organic and conventional grain crops in a long-term agroecological research (LTAR) site in Iowa. *J. of Altern. Agric.***18:** 59–69.

Döring, T. F., and Kromp, B. 2003.Which carabid species benefit from organic agriculture? A review of comparative studies in winter cereals from Germany and Switzerland. *Agric. Ecosys. & Environ*. **98:** 153–161.

Drinkwater, L. E., Wagoner, P., and Sarrantonio, M. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* **396:** 262–265.

Duelli, P., and Obrist, M. K. 2003. Biodiversity indicators: The choice of values and measures. *Agric. Ecosys. & Environ.* **98:** 87–98.

EC (European Commission) 2007. Council Regulation (EC) No 834/2007, of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092. Internet http://eurlex.europa.eu/LexUriServ/site/en/oj/2007/l_189/l_18920070720en 00010023.pdf. Accessed on 25 November 2009.

Edwards-Jones, G., and Howells, O. 2001. The origin and hazard of inputs to crop protection in organic farming systems: Are they sustainable? *Agricultural Sys.* **67:** 31–47.

Ehrlich, P., and Ehrlich, A. 1981. *Extinction: The Causes and Consequences of the Disappearance of Species*. Random House, New York.

Ekroos, J., Hyvönen, T., Tiainen, J., and Tiira, M. 2010. Responses in plant and carabid communities to farming practises in boreal landscapes. *Agric. Ecosys. & Environ.* **135:** 288–293.

El-Hage Scialabba, N. 2007. Organic agriculture and food security. International Conference on Agriculture and Food Security, FAO, Rome. ftp://ftp.fao.org/paia/organicag/ofs/OFS-2007-5.pdf. Accessed on 20 May 2010.

El-Hage Scialabba, N., and Müller-Lindenlauf, M. 2010. Organic agriculture and climate change. *Renewable Agriculture and Food Systems* **25:** 158–169.

Elliot, S.L., and Mumford, J.D. 2002. Organic, integrated and conventional apple production: Why not consider the middle ground? *Crop Protection* **21:** 427–429.

Enserink, M. 2010. Tough lesson from golden rice. *Science* **320:** 468–471.

Eyhorn, F., Ramakrishnan, M., and Mäder, P. 2007. The viability of cotton-based organic agriculture systems in India. *Int. J. Agric. Sust.* **5:** 25–38.

FAO. 2002. *Organic Agriculture, Environment and Food Security.* Environment and Natural Resources Service Sustainable Development Department. http://www.fao.org/DOCREP/005/Y4137E/y4137e00.htm#TopOfPage. Accessed on 12 January 2009.

FAO. 2004. *The Scope of Organic Aagriculture, Sustainable Forest Management and Ecoforestry in Protected Area Management*. FAO, Rome. http://www.fao.org/docrep/007/y5558e/y5558e00.htm#toc. Accessed on November 15, 2009.

FAO. 2006. *Livestock's Long Shadow*. FAO, Rome. ftp://ftp.fao.org/docrep/fao/010/A0701E/A0701E00.pdf Accessed on 20 November 2009.

FAO. 2008. The state of food insecurity in the developing world. FAO, Rome. http://www.fao.org/docrep/012/i0876e/i0876e00.HTM Accessed on January 20, 2010.

Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M. A., Munch, J. C., and Beese, F. 2002. Integrated evaluation of greenhouse gas emissions (CO2, CH4, N2O) from two farming systems in southern Germany. *Agric. Ecosyst. & Environ.* **91:** 175–189.

Fließbach, A., and Mäder, P. 2000. Microbial biomass and size-density fractions differ between soils of organic and conventional agricultural systems. *Soil Biol. Biochem.* **32:** 757–768.

Fließbach, A, Mäder, P., and Niggli, U. 2000. Mineralization and microbial assimilation of ^{14}C-labeled straw in soils of organic and conventional agricultural systems. *Soil Biology & Biochem.* **32:** 1131–1139.

Fließbach, A., Oberholzer, H. R., Gunst, L., and Mäder, P. 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. *Agric. Ecosyst. & Environ.* **118:** 273–284.

Fluck, R. C. and Baird, C. D. 1980. *Agricultural Energetics*. Avi Publishing Company Inc., Westport, CT, USA.

Foereid, B., and Høgh-Jensen, H. 2004. Carbon sequestration potential of organic agriculture in northern Europe – a modelling approach. *Nutr. Cycl. in Agroecosyst.* **68:** 13–24.

Foley, J. A., DeFries, R., Asner, G. P., Barford. C., and fifteen other. 2005. Global consequences of land use. *Science* **309:** 570–574.

Foster, C., Green, K., Bleda, M., Evans, B., Flynn, A., and Myland, J. 2006. *Environmental Impact of Food Production and Consumption*. A report to the Department of Environment, Food and Rural Affair (DEFRA). Manchester Business School, DEFRA, London. http://www.defra.gov.uk/science/project_data/DocumentLibrary/EV02007/EV02007_4601_FRP.pdf Accessed on 20 June 2010.

Fuller R. J., Norton L. R., Feber R. E., Johnson P. J., Chamberlain D. E., Joys A. C., Mathews F., Stuart R. C., Townsend M. C., Manley W. J., Wolfe M. S., Macdonald D. W., and Firbank L. G. 2005. Benefits of organic farming to biodiversity vary among taxa. *Biol. Lett.* **1:** 431–434.

Gabriel, D., Roschewitz, I., Tscharntke, T., and Thies, C. 2006. Beta diversity at different spatial scales: Plant communities in organic and conventional agriculture. *Ecol. Appl.* **16:** 2011–2021.

Gabriel, D., Sait, S. M., Hodgson, J. A., Schmutz, U., Kunin, W. E., and Benton, T. G. 2010. Scale matters: The impact of organic farming on biodiversity at different spatial scales. *Ecology Letters* **13:** 858–869.

Gardiner, M. M., Landis, D. A., Gratton, C., DiFonzo, C. D., O'Neal, M., Chacon, J. M., Wayo, M. T., Schmidt, N. P., Mueller, E. E., Heimpel, G. E. 2009. Landscape diversity enhances biological control of an introduced crop pest in the north-central USA. *Ecological Applications* **19:** 143–154.

Gaston, K. J., and Spicer, J. I. 2004. *Biodiversity. An Introduction*. Blackwell Publishing, Oxford, UK.

Gelfand, I., Snapp, S., and Robertson, G. P. 2010. Energy efficiency of conventional, organic, and alternative cropping systems for food and fuel at a site in the U.S. Midwest. *Environmental Science & Technology* **44:** 4006–4011.

Giampietro, M. 2004. *Multi-Scale Integrated Analysis of Agroecosystems*. CRC Press, Boca Raton, London.

Giampietro, M. and Mayumi, K. 2009. *The Biofuel Delusion: The Fallacy of Large Scale Agro-biofuels Production*. Earthscan, London.

Giampietro, M., Pimentel, D., and Cerretelli, G. 1992. Energy analysis of agricultural ecosystem management: Human return and sustainability. *Agric. Ecosyst. & Environ.* **38:** 219–244.

Giampietro, M. and Ulgiati, S. 2005. An integrated assessment of large-scale biofuel production. *Critical Review in Plant Sciences* **24:** 1–20.

Gibson, R. H., Pearce, S., Morris, R. J., Symondson, W. O. C., and Menmott, J. 2007. Plant diversity and land use under organic and conventional agriculture: A whole-farm approach. *J. Appl. Ecol.* **44:** 792–803.

Gliessman, S. R. 2007. *Agroecology: Ecological Processes in Sustainable Agriculture*. (2nd ed.) Lewis Publisher, Boca Raton, New York.

Global Footprint Network (2009). World Footprint: Do we fit on the planet? http://www.footprintnetwork.org/en/index.php/GFN/page/world_footprint/ Accessed on the 23 April 2010.

Glover, J. D., Reganold, J. P., and Andrews, P. K. 2000. Systematic method for rating soil quality of conventional, organic,and integrated apple orchards in Washington State. *Agric. Ecosyst. Environ.* **80:** 29–45.

Gold, M. V., and Gates J. P. 2007. Tracing the evolution of organic/sustainable agriculture: A selected and annotated bibliography. http://www.nal.usda.gov/afsic/pubs/tracing/tracing.shtml Accessed on 20 January 2010.

Gomiero, T., Giampietro, M., and Mayumi, K. 2006. Facing complexity on agro-ecosystems: a new approach to farming system analysis. *Int. J. of Agric. Res. Gov. and Ecol.* **5:** 116–144.

Gomiero, T., Paoletti, M. G., Pimentel, D. 2008. Energy and environmental issues in organic and conventional agriculture. *Crit. Rev. Plant Sci.* **27:** 239–254.

Gomiero, T., Paoletti, M.G. and Pimentel, D. 2010. Biofuels: Ethics and concern for the limits of human appropriation of ecosystem services. *Journal of Agriculture and Environmental Ethics* **23:** 403–434.

Gold, M. V. 2007. Organic production. U.S. Department of Agriculture http://www.ers.usda.gov/data/organic/ Accessed on 20 June 2010.

Gotelli, N. J., and Colwell, R. K. 2001. Quantifying biodiversity: Procedures and pitfalls in the measurement and comparison of species richness. *Ecol. Lett.* **4:** 379–391.

Grandy, S. A., and Robertson, G. P. 2007. Land-use intensity effects on soil. *Ecosystems* **10:** 58–73.

Green, R. E., Cornell, S. J., Scharlemann, J. P. W., and Balmford, A. 2004. Farming and the fate of wild nature. *Science* **307:** 550–555.

Gunapala, N., and Scow, K. M. 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming systems. *Soil Biol. Biochem.* **30:** 805–816.

Gündomuþ, E. 2006. Energy use on organic farming: A comparative analysis on organic versus conventional apricot production on small holdings in Turkey. *Energy Conservation and Management* **47:** 3351–3359.

Guthman, J. 2004. *Agrarian Dreams: The Paradox of Organic Farming in California*. University of California Press, Los Angeles.

Guzmán, G. I., and Alonso, A. M. 2008. A comparison of energy use in conventional and organic olive oil production in Spain. *Agricultural Systems* **98:** 167–176.

Haas, G., Wetterich, F., and Kopke, U. 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Agric., Ecosys. and Environ.* **83:** 43–53.

Hajjar, R., Jarvis, D. I., and Gemmill-Herren, B. 2008. The utility of crop genetic diversity in maintaining ecosystem services. *Agr. Ecosyst. & Environ.* **123:** 261–270.

Halberg, N., Alroe, H. F., Knudsen, M. T., and Kristensen, E. S. (Eds.) 2006. *Global Development of Organic Agriculture: Challenges and Prospects*. CABI Publishing.

Hamilton, G. 2000. When good bugs turn bad. *New Scientist* **15 January:** 30–33.

Hansen, B., Alrøe, H. F., and Kristensen, E. S. 2001. Approaches to assess the environmental impact of organic farming with particular regard to Denmark. *Agric. Ecosyst. & Environ.* **83:** 11–26.

Hawesa, C., Squirea, G. R., Hallett, P. D., Watsonb, C. A., and Young, M. 2010. Arable plant communities as indicators of farming practice. *Agric. Ecosyst. & Environ.* **138:** 17–26.

Heckman, J. 2006. A history of organic farming transitions from Sir Albert Howard's war in the soil to the USDA National Organic Program. *Renewable Agriculture and Food Systems* **21:** 143–150.

Hendrix, J. 2007. Editorial response by Jim Hendrix. *Renew. Agric. and Food Syst.* **22:** 84–85.

Hillel, D. 1991. *Out of the Earth. Civilization and the Life of the Soil.* California Univ. Press, CA.

Hoeppner, J. W., Entz, M. H., McConkey, B. G., Zentner, R. P., and Nagy, C. N. 2005. Energy use and efficiency in two Canadian organic and conventional crop production systems. *Renewable Agriculture and Food Systems* **21:** 60–67.

Hole, D. G., Perkins A. J., Wilson J. D., Alexander I. H., Grice P. V., and Evans A. D. 2005. Does organic farming benefit biodiversity? *Biol. Conserv*. **122**:113–130.

Holland, J. M. 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agric., Ecosys. and Environ.* **103:** 1–25.

Holzschuh, A., Steffan-Derwenter, I., Kleijn, D., amd Tscharntke, T. 2007. Diversity of flower-visiting bees in cereal fields: Effects of farming system, landscape composition and regional context. *J. Appl. Ecol.* **44:** 41–49.

Holzschuh, A., Steffan-Dewenter, I., and Tscharntke, T. 2008. Agricultural landscapes with organic crops support higher pollinator diversity. *Oikos* **117:** 354–361.

Howard, A. 1943. *An Agricultural Testament*. Oxford University Press, London. Available on internet at URL: http://journeytoforever.org/farm_library/howardAT/ATtoc.html

Hsu, Y.-T., Shen, T.-C., and Hwang S.-Y. 2009. Soil fertility management and pest responses: A comparison of organic and synthetic fertilization. *J. Econ. Entomol.* **102:** 160–169.

Hyvönen, T. 2007. Can conversion to organic farming restore the species composition of arable weed communities? *Biological Conservation* **137:** 328–390.

Hyvönen, T., Ketoj, E., Salonen, J., Jalli, H., and Tiainen, J. 2003. Weed species diversity and community composition in organic and conventional cropping of spring cereals. *Agric. Ecosys. & Environ*. **97:** 131–149.

Hyvönen, T., and Salonen, J. 2002. Weed species diversity and community composition in cropping practices at two intensity levels – a six-year experiment. *Plant Ecology* **154:** 73–81.

Hudson Institute 2007. *"Organic Abundance" Report: Fatally Flawed*. http://www.cgfi.org/cgficommentary/organic-abundance-report-fatallyflawed/. Accessed on 2 May 2010.

IFOAM (International Movement of Organic Agriculture Movements), 2008. *The World of Organic Agriculture - Statistics and Emerging Trends 2008*. International Federation of Organic Agriculture Movements -IFOAM, Bonn, Germany.

IFOAM (International Movement of Organic Agriculture Movements), 2010. Definition of Organic Agriculture. IFOAM http://www.ifoam.org/growing_organic/definitions/doa/index.html, and http://www.ifoam.org Accessed on 10 March 2010.

IPCC (Intergovernmental Panel on Climate Change). 2000. *Emissions Scenarios*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Nakicenovic, N., and Swart, R., Eds. Available on internet at URL http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0 Accessed on 20 May 2010.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available on internet at URL http://www.ipcc.ch/. Accessed on 20 May 2010.

Janzen, H. H. 2004. Carbon cycling in earth systems—a soil science perspective. *Agric., Ecosys. & Environ.* **104:** 399–417.

Kasperczyk, N., and Knickel, K. 2006. Environmental impact of organic agriculture. **In:** *Organic Agriculture. A Global Perspective*. pp. 259–294. Kristiansen, P., Taji, A., Reganold, J., Eds., CSIRO Publishing, Collingwood, Australia.

Kennedy, T. A., Naeem, S., Howe, K. M., Knops, J. M. H., Tilman, D., and Reich, P. 2002. Biodiversity as a barrier to ecological invasion. *Nature* **417:** 636–638.

Keoleian, H. and Keoleian, G. A. 2000. *Life Cycle-Based Sustainability Indicators for Assessment of the U.S. Food System*. The University of Michigan, Center for Sustainable Systems, Ann Arbor, MI. http://css.snre.umich.edu/css_doc/CSS00-04.pdf Accessed on 20 June 2010.

Kern, J. S., and Johnson, M. G. 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. *Soil Sci. Soc. Am.* **57:** 200–210.

Kirchmann, H., Bergström, L., Kätterer, T., Mattsson, L., and Gesslein, S. 2007. Comparison of long-term organic and conventional crop–livestock systems on a previously nutrient-depleted soil in Sweden. *Agron. J.* **99:** 960–972.

Kirchmann, H., and Thorvaldsson, D. 2000. Challenging targets for future agriculture. *European Journal of Agronomy* **12:** 145–161.

Koepf, H. H. 1976. *Biodynamic Agriculture: An Introduction.* The Anthroposofic Press, Spring Valley, New York. Available at URL: http://continuousharvest.com/Documents/Bio-Dynamic%20Agriculture%20book.pdf

Koepf, H. H. 2006. *The Biodynamic Farm*. Steiner Books, Dulles, VA.

Koh, L. P., Dunn, R. R., Sodhi, N. S., Colwell, R. K., Proctor, H. C., and Smith, V. S. 2004. Species coextinctions and the biodiversity crisis. *Science* **305:** 1632–1634.

Koneswaran, G. and Nierenberg, D. 2008a. Global farm animal production and global warming: impacting and mitigating climate change. *Environ. Health Perspect*. **116:** 578–582.

Koneswaran, G. and Nierenberg, D. 2008b. Beef production: Koneswaran and Nierenberg respond. *Environ. Health Perspect.* **116:** 365–376.

Kramer, S. B., Reganold, J. P., Glover, J. D., Bohannan, B.J.M., and Mooney, H. A. 2006. Reduced nitrate leaching and enhanced denitrifier activity and efficiency in organically fertilized soils. *PNAS* **103:** 4522–4527.

Krebs, J. R., Wilson, J. D., Bradbury, R. B., and Siriwardena, G. M. 1999. The second Silent Spring? *Nature* **400:** 611–612.

Kristiansen, P., Taji, A., and Reganold, J. (Eds.) 2006. *Organic Agriculture. A Global Perspective*. CSIRO Publishing, Collingwood, Australia.

Kruess, A., and Tscharntke, T. 1994 Habitat fragmentation, species loss, and biological control. *Science* **264:** 1581–1584.

Küstermann, B., Kainz, M., and Hülsbergen, K.-J. 2008. Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. *Renewable Agriculture and Food Systems* **23:** 38–52.

Küstermann, B., Christen, O., and Hülsbergen, K-J. 2010. Modelling nitrogen cycles of farming systems as basis of site- and farm-specific nitrogen management. *Agric. Ecosys. & Environ.* **135:** 70–80.

Lal, R. 2004. Soil carbon sequestration impact on global climate and food security. *Science* **304:** 1623–1627.

Lal, R. 2010. Enhancing eco-efficiency in agro-ecosystems through soil carbon sequestration. *Crop Sci.* **50:** 120–131.

Lamine, C., and Bellon, S. 2009. Conversion to organic farming: A multidimensional research object at the crossroads of agricultural and social sciences. A review. *Agron. Sustain. Dev.***29:** 97–112.

Lampkin, N. 2002. *Organic Farming.* (Revised edition). Old Pond Publishing, Suffolk, UK.

Lavelle, P., and Spain, A. V. 2002. *Soil Ecology*. Kluwer Academic Publishers, Amsterdam.

Letourneau, D. K. and Goldstein, B. 2001. Pest damage and arthropod community structure in organic vs. conventional tomato production in California. *J. Appl. Ecol.* **38:** 557–570.

Letourneau, D. K., and Bothwell, S. G. 2008. Comparison of organic and conventional farms: challenging ecologists to make biodiversity functional. *Frontiers in Ecology and the Environment* **6:** 430–438.

Liebman, M., Gibson, L. R., et al. 2008. Agronomic and economic performance characteristics of conventional and low-external-input cropping systems in the Central Corn Belt. *Agron. J.* **100:** 600–610.

Liu, B. Tu, C., Hu, S., Gumpertz, M., and Ristaino, J. B. 2007. Effect of organic, sustainable, and conventional management strategies in grower fields on soil physical, chemical, and biological factors and the incidence of Southern blight. *Appl. Soil Ecol.* **37:** 202–214.

Lockeretz, W. (Ed.) 2007. *Organic Farming: An International History*. CABI, Cambridge, MA.

Lockeretz, W., Shearer, G., and Kohl, D. H. 1981. Organic farming in the Corn Belt. *Science* **211:** 540–546.

Lohr, L., and Park, T. A.,2007. Efficiency analysis for organic agricultural producers: The role of soil-improving inputs. *J. Environ. Manag.* **83:** 25–33.

Loreau, M., Naeem, S., and Inchausti, P. (Eds). 2002. *Biodiversity and Ecosystem Functioning: Synthesis and Perspectives*. Oxford University Press, Oxford.

Losey, J. E., and Vaughan, M. 2006. The economic value of ecological services provided by insects. *BioScience* **56:** 311–323.

Lotter, D. W. 2003. Organic agriculture. *J. of Sust. Agric.* **21:** 59–128.

Lotter, D. W., Seidel, R., and Liebhart, W. 2003. The performance of organic and conventional cropping systems in an extreme climate year. *Am. J. Alternative Agriculture* **18:** 146–154.

Luck, G. W., Harrington, R., et al. 2009. Quantifying the contribution of organisms to the provision of ecosystem services. *BioScience* **59:** 223–235.

Lund, V. 2006. Natural living—a precondition for animal welfare in organic farming. *Livestock Science* **100:** 71– 83.

Lynch, D. H., MacRae, R., and Marti, R. C. 2011. The Carbon and global warming potential impacts of organic farming: Does it have a significant role in an energy constrained world? *Sustainability* **3:** 322–362.

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. 2002a. Soil fertility and biodiversity in organic farming. *Science* **296:** 1694–1697.

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. 2002b. The ins and outs of organic farming. *Science* **298:** 1889–1890.

Mahoney P. R., Olson, K. D., Porter, P. M., Huggins, D. R., Perillo, C. A., and Crookston, C. K. 2004. Profitability of organic cropping systems in Southwestern Minnesota. *Renewable Agriculture and Food Systems* **19:** 35–46.

Marinari, S., Mancinelli, R., Campiglia, E., and Grego, S. 2006. Chemical and biological indicators of soil quality in organic and conventional farming systems in Central Italy. *Ecological Indicators* **6:** 701–711.

Marriott, E. E., and Wander, M. 2006. Qualitative and quantitative differences in particulate organic matter fractions in organic and conventional farming systems. *Soil Biol. & Biochem.* **38:** 1527–1536.

Mathieu, O., Lévêque, J., Hénault, C., Milloux, M.-J., Bizouard, F., and Andreux, F. 2006. Emissions and spatial variability of N2O, N2 and nitrous oxide mole fraction at the field scale, revealed with 15N isotopic techniques. *Soil Biol. & Biochem.* **38:** 941–951.

Matson, P. A., Naylor, R. L., and Ortiz-Monasterio, I. 1998. Integration of environmental, agronomic, and economic aspect of fertilizer management. *Science* **280**:112–115.

Matson, P. A., Parton, W. J., Power, A. G., and Swift, M.J. 1997. Agricultural intensification and ecosystem properties. *Science* **277:** 504–509.

McCandless, M., Venema, H. D., Barg, S., and Oborne, B. 2008. *Full Cost Accounting for Agriculture*. International Institute for Sustainable Development. http://www.iisd.org/pdf/2008/measure_fca_2008.pdf Accessed on 20 January 2010.

McDonald, A. J., Hobbs, P. R., and Riha, S. J. 2005. Does the system of rice intensification outperform conventional best management? A synopsis of the empirical record. *Field Crops Res.* **96:** 31–36.

Millennium Ecosystem Assessment. 2005a. *Millennium Ecosystem Assessment: Vol. 2, Scenario assessment*. http://www.millenniumassessment.org/en/Scenarios.aspx Accessed 25 November 2009.

Millennium Ecosystem Assessment. 2005b. *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington, DC. http://www.millenniumassessment.org/en/Synthesis.aspx Accessed 25 November 2009.

Molden, D. (Ed.). 2007. *Water for Food, Water for Life. A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London. The publication is available on internet at URL: http://www.iwmi.cgiar.org/assessment/Publications/books.htm

Mols, C. M. M., and Visser, M. E. 2002. Great Tits can reduce caterpillar damage in apple orchards. *J. Appl. Ecol.* **39:** 888–899.

Mols, C. M. M., and Visser, M. E. 2007. Great Tits (*Parus major*) reduce caterpillar damage in commercial apple orchards. *PLoS ONE* **2:** e202.

Montgomery, D. R. 2007a. Soil erosion and agricultural sustainability. *PNAS* **104**:13268–13272.

Montgomery, D. R. 2007b. *Dirt: The Erosion of Civilization*. University of California Press, Berkeley.

Moreby, S. J., Aebischer, N. J., Southway, S. E., and Sotherton, N. W. 1994. A comparison of the flora and arthropod fauna of organically and conventionally grown winterwheat in southern England. *Annals Applied Biol.* **125:** 13–27.

Morison, J. I. L., Baker, N. R., Mullineaux, P. M., and Davies, W. J. 2008. Improving water use in crop production. *Phil. Trans. B* **363:** 639–658.

Müller-Lindenlauf, M., Deittert, C., and Köpke, U. 2010. Assessment of environmental effects, animal welfare and milk quality among organic dairy farms. *Livestock Science* **128:** 140–148.

Murphy, J. D. 2007. *People, Plant & Genes*. Oxford University Press, New York.

Nemes, N. 2009. Comparative analysis of organic and non-organic farming systems: A critical assessment of farm profitability. Food and Agriculture Organization of the United Nations, Rome, June 2009. ftp://ftp.fao.org/docrep/fao/011/ak355e/ak355e00.pdf

Niggli, U., Earley, J., and Ogorzalek, K. 2007. Organic agriculture and environmental stability of the food supply. International Conference on Agriculture and Food Security, FAO Rome. ftp://ftp.fao.org/docrep/fao/meeting/012/ah950e.pdf Accessed 24 October 2009.

Niggli U., Slabe A., Schmid O., Halberg N., and Schlüter M. 2008. Vision for an organic food and farming research agenda to 2025 organic knowledge for the future. IFOAM http://www.tporganics.eu/upload/TPOrganics_VisionResearchAgenda.pdf Accessed on 20 August 2009.

Niggli, U., Fließbach, A., Hepperly, P. and Scialabba, N. 2009. Low greenhouse gas agriculture: mitigation and adaptation potential of sustainable farming systems. FAO, Rome. April 2009, Rev. 2 – 2009. ftp://ftp.fao.org/docrep/fao/010/ai781e/ai781e00.pdf Accessed on 20 May 2010.

Noe, E., Halberg, N, and Reddersen, J. 2005. Indicators of biodiversity and conservational wildlife quality on Danish organic farms for use in farm management: A multidisciplinary approach to indicator development and testing. *J. Agric. and Environ. Ethics* **18:** 383–414.

NRC (National Research Council). 2010. *Toward Sustainable Agricultural Systems in the 21st Century.* National Academies Press http://www.nap.edu/catalog/12832.html Accessed on 20 March 2010.

Norton, L., Johnson, P., Joys, A., Stuart, R., et al. 2009. Consequences of organic and non-organic farming practices for field, farm and landscape complexity. *Agric. Ecosys & Environ.* **129:** 221–227.

Organic World, 2008. http://www.organic-world.net/. Accessed on March 16, 2008.

Pacini, C., Wossink, A., Giesen, G., Vazzana, C., and Huirne, R. 2003. Evaluation of sustainability of organic, integrated and conventional farming systems: a farm and field-scale analysis. *Agric. Ecosys & Environ* **95:** 273–288.

Paoletti, M. G. 1999. Using bioindicators based on biodiversity to assess landscape sustainability. *Agric. Ecosys & Environ.* **74:** 1–18.

Paoletti, M. G., and Lorenzoni, G. G. 1989. Agroecology patterns in Northeastern Italy. *Agric. Ecosys. & Environ.* **27:** 139–154.

Paoletti, G. M., and Pimentel, D. (Eds). 1992. *Biotic Diversity in Agroecosystems*. Elsevier, Amsterdam.

Paoletti, M. G., Schweigl, U., and Favretto, M. R.1995. Soil macroinvertebrates, heavy metals and organochlorines in low and high input apple orchards and a coppiced woodland. *Pedobiologia* **39:** 20–33.

Paoletti, M. G., Boscolo, P., and Sommaggio, D. 1997. Predators-parasitoids and beneficial insects in fields sorrounded by hedgerows in North Eastern Italy. *Biological Agriculture and Horticulture* **15:** 311–323.

Paoletti, M. G., Thomson, L. J., and Hoffmann, A. (Eds.) 2007a. Using invertebrate bioindicators to assess agricultural sustainability in Australia: Proposals and current practices. *Experimental Journal of Australian Agriculture* **47**(special issue): 379–478.

Paoletti M. G., Tsitsilas A., Thomson L. J., Taiti S., Umina, P. A. 2007b. The flood bug, *Australiodillo bifrons* (Isopoda: Armadillidae): A potential pest of cereals in Australia? *Appl. Soil Ecol.* **39**:76–83.

Paoletti, M. G., Sommaggio, D., Favretto, M. R., Petruzzelli, G., Pezzarossa, B., and Barbafieri, M. 1998. Earthworms as useful bioindicators of agroecosystem sustainability in different input orchards. *Appl. Soil Ecol.* **10:** 137–150.

Pelletier, N., Arsenault, N., and Tyedmers, P. 2008. Scenario modeling potential eco-efficiency gains from a transition to organic agriculture: Life cycle perspectives on Canadian canola, corn, soy, and wheat production. *Environ. Manage.* **42:** 989–1001.

Perfecto, I., Vandermeer, J. H., Bautista, G. L., Nunez, G. I., Greenberg, R., Bichier, P., and Langridge, S. 2004. Greater predation in shaded coffee farms: The role of resident neotropical birds. *Ecology* **85:** 2677–2681.

Petersen, S. O., Regina, K., Pöllinger, A., Rigler, E., Valli, L., Yamulki, S., Esala, M., Fabbri, C., Syväsalo, E., and Vinther, F. P. 2006. Nitrous oxide emissions from organic and conventional crop rotations in five European countries. *Agric. Ecosys. & Environ.* **112:** 200–206.

Pfiffner, L., and Niggli, U. 1996. Effects of bio-dynamic, organic and conventional farming on ground beetles (Col. Carabidae) and other Epigaeic arthropods in winter wheat. *Biological Agriculture and Horticulture* **12:** 353–364.

Pfiffner, L. and Mäder, P. 1997. Effects of biodynamic, organic and conventional production systems on earthworm populations. Entomological research in organic agriculture. *Biological Agriculture and Horticulture* **15:** 3–10.

Pfiffner, L., and Luka, H. 2003. Effects of low-input farming systems on carabids and epigeal spiders—a paired farm approach. *Basic Appl. Ecol.* **4:** 117–127.

Pfiffner, L., and Luka, H. 2007. Earthworm populations in two low-input cereal farming systems. *Appl. Soil Ecol.* **37:** 184–191.

Pfiffner, L., Häring, A., Dabbert, S., Stolze, M., and Piorr, A. 2001. Contributions of organic farming to a sustainable environment. http://orgprints.org/2943/1/pfiffner-2001-proceedings-copenhagen.pdf Accessed on 20 May 2010.

Phelan, P. L. 2009. Ecology-based agriculture and the next green revolution. **In:** *Sustainable Agroecosystem Management*, pp. 97–135. Bohlen, P. J., and House, G., Eds, CRC Press, Boca Raton, FL.

Phelan, P. L., Mason, J. F., and Stinner, B.R. 1995. Soil-fertility management and host preference by European corn borer, *Ostrinia nubilalis* (Hübner), on *Zea mays* L.: A comparison of organic and conventional chemical farming. *Agric. Ecosys. & Environ.* **56:** 1–8.

Phelan, P. L., Norris, K. H., and Mason, J. F. 1996. Soil-management history and host preference by *Ostrinia nuhilalis:* Evidence for plant mineral balance mediating insect-plant interactions. *Environ. Entomol*. **25**:1329–1336.

Pimentel, D. 1989. Energy flow in food system. **In:** *Food and Natural Resources*. pp. 1–24. Pimentel, D., and Hall, C. W. Eds. Academic Press, New York.

Pimentel, D. 1997. *Technique for Reducing Pesticides Use. Economic and Environmental Benefits*. J.Wiley & Sons, New York.

Pimentel, D. 2006. *Impacts of Organic Farming on the Efficiency of Energy Use in Agriculture: An Organic Center State of Science Review*. (The Organic Center). Internet http://www.organic-center.org/reportfiles/ENERGY_SSR.pdf. Accessed on 12 January 2008.

Pimentel, D. and Patzek, T. 2005. Ethanol production using corn, switchgrass, and wood: biodiesel production using soybean and sunflower. *Natural Resources Research* **14:** 65–76.

Pimentel, D., and Pimentel, M. 2008. *Food, Energy, and Society. 3^d* ed. CRC Press, Boca Raton, FL.

Pimentel, D., Berardi, G., and Fast, S. 1983. Energy efficiency of farming systems: Organic and conventional agriculture. *Agric. Ecosys. & Environ.* **9:** 359–372.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M, Crist, S., Sphpritz, L., Fitton, L., Saffouri, R., and Blair, R. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* **267:** 1117–1123.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., and Seidel, R. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. *BioScience* **55:** 573–582.

Pimentel, D., Hurd, E., Bellotti, A. C., Forster, M. J., Oka, I. N., Sholes, O.D., and Whitman, R. J. 1973. Food production and the energy crisis. *Science* **182:** 443–449.

Pimentel, D., Petrova, T., Riley, M., Jacquet, J., Ng, V., Honigman, J., and Valero, E. 2006. Conservation of biological diversity in agricultural, forestry, and marine systems. **In:** *Focus on Ecology Research*. pp. 151–173, Burk, A. R., Ed., Nova Science Publishers, New York. Also, 2007. **In:** *Focus on Biodiversity Research*. pp. 1–25. Schwartz, J., Ed., Nova Science Publishers, New York.

Pimentel, D., Stachow, U., Takacs, D. A., Brubaker, H. W., Dumas, A. R., Meaney, J. J., O'Neill, J. A. S., Onsi, D. E. and Corzelius, D. B. 1992 Conserving biological diversity in agricultural/forestry systems. *Bioscience* **432:** 354–362.

Pimentel, D., Wilson, C., McCullum, C., Huang, R., Dwen, P., Flack, J., Tran, Q., Saltman, T., and Cliff, B., 1997. Economic and environmental benefits of biodiversity. *BioScience* **47:** 747–757.

Pocock, M.J. O., and Jennings, N. 2007. Testing biotic indicator taxa: The sensitivity of insectivorous mammals and their prey to the intensification of lowland agriculture. *J. Appl. Ecol.***45:** 151–160.

Pretty, J. 2002. Lessons from certified and non certified organic projects in developing countries. **In:** *Organic Agriculture, Environment and Food Security*. pp. 139–162. El-Hage Scialabba, N., and Hattam, C., Eds., FAO, Rome, Italy.

Pretty, J., and Hine, R. 2001. *Reducing Food Poverty with Sustainable Agriculture: A Summary of New Evidence*. Final report from the 'SAFE World' Research Project, University of Essex. Internet http://www.essex.ac.uk/ces/esu/occasionalpapers/SAFE%20FINAL%20-%20Pages1-22.pdf. Accessed on 12 February 2010.

Pretty, J. N., Ball, A. S., Lang, T., and Morison, J. I. L. 2005. Farm costs and food miles: An assessment of the full cost of the UK weekly food basket. *Food Policy* **30:** 1–19.

Pretty, J. N., Ball, A. S., Xiaoyun, L., and Ravindranath, N. H. 2002. The role of sustainable agriculture and renewable-resource management in reducing greenhouse-gas emissions and increasing sinks in China and India. *Phil. Trans. A* **360:** 1741–1761.

Pretty, J. N., Brett, C., Gee, D., Hine, R. E., Mason, C. F., Morison, J. I. L., Raven, H., Rayment, M. D., and van der Bijl, G. 2000. An assessment of the total cost of external costs of UK agriculture. *Agricultural Systems* **65:** 113–136. Pretty, J. N., Mason, C. F., Nedwell, D. B., Hine, R. E., Leaf, S. and Dils, R. 2003. Environmental costs of the eutrophication of the fresh waters in England and Wales. *Environ. Sci. & Technol.* **37:** 201–208.

Pretty, J. N., Noble, A. D., Bossio, D., Dixon. J., Hine, R. E., Penning derVires, F. V. T., and Morrison J. I. L. 2006. Resource-conserving agriculture increases yields in developing countries. *Environ. Sci. & Technol.* **40:** 1114–1119.

Purtauf, T., Roschewitz, I., Dauber, J., Thies, C., Tscharntke, T. and Wolters, V. 2005. Landscape context of organic and conventional farms: Influences on carabid beetle diversity. *Agric. Ecosys. & Environ.* **108:** 165–174.

Quinton, J. N., Govers, G., Van Oost, C., and Bardgett, R. D. 2010. The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience* **3:** 311–314.

Rasmussen, P. E., Goulding, K.W. T., Brown, J. R., Grace, P. R., Janzen, H. H., and Körschens, M. 1998. Long-term agroecosystem experiments: Assessing agricultural sustainability and global change. *Science* **282:** 893–896.

Refsgaard, K., Halberg, N., and Kristensen, E. S. 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. *Agricultural Systems* **57:** 599–630.

Reganold, J. P. 1995. Soil quality and profitability of biodynamic and conventional farming systems: A review. *Am. J. Alternative Agric.* **10:** 36–46.

Reganold, J., Elliott, L., and Unger, Y. 1987. Long-term effects of organic and conventional farming on soil erosion. *Nature* **330:** 370–372.

Reganold, J., Glover, J., Andrews, P., and Hinman, H. 2001. Sustainability of three apple production systems. *Nature* **410:** 926–929.

Rigby, D., and Càceres, D. 2001. Organic farming and the sustainability of agricultural systems. *Agricultural Systems* 68: 21–40.

Robertson, G. P., and Vitousek, P. M., 2009. Nitrogen in agriculture: Balancing the cost of an essential resource. *Annu. Rev. Environ. Res.* **34:** 97–125.

Rodale, J. I. 1945. *Pay Dirt: Farming & Gardening With Composts*. Devin-Adair Co., New York.

Roschewitz, I., Gabriel, D., Tscharntke T., and Thies, T., 2005. The effects of landscape complexity on arable weed species diversity in organic and conventional farming. *J. Appl. Ecol.* 42: 873–882.

Rundlöf, M., Bengtsson, J., and Smith, H. G. 2008. Local and landscape effects of organic farming on butterfly species richness and abundance. *J. Appl. Ecol.* **45:** 813–820.

Rundlöf, M., and Smith, H. G. 2006. The effect of organic farming on butterfly diversity depends on landscape context. *J. Appl. Ecol.* **43:** 1121–1127.

Russo, M. A., Belligno, A., Wu, J. Y., and Sardo, V. 2010. Comparing mineral and organic nitrogen fertilizer impact on the soil-plant-water system in a succession of three crops. *Recent Research in Science and Technology* **2:** 14–22.

Saunders, C., Barber, A., and Taylor, G. 2006. *Food Miles – Comparative Energy/Emissions Performance of New Zealand's Agriculture Industry*. Research Report No. 285 Agribusiness & Economics Research Unit, Lincoln University, New Zealand. http://www.jborganics.co.nz/saunders_report.pdf Accessed on 20 July 2010.

Schlesinger, W. H. 1999. Carbon and agriculture: Carbon sequestration in soils. *Science* **284:** 2095.

Schlich, E., and Fleissner, U. 2005. The ecology of scale: Assessment of regional energy turnover and comparison with global food. *The International Journal of Life Cycle Assessment* **10:** 213–223.

Schmidt, M. H., Roschewitz, I., Thies, C., and Tscharntke, T. 2005. Differential effects of landscape and management on diversity and density of ground-dwelling farmland spiders. *J. Appl. Ecol.* **42:** 281–287.

Shepherd, M., Pearce, B., Cormack, B., Philipps, L., Cuttle, S., Bhogal, A., Costigan, P., Unwin, R. 2003. *An Assessment of the Environmental Impacts of Organic Farming*. Department for Environment, Food and Rural Affairs UK. http://orgprints.org/6784/2/OF0405_909_TRP.pdf Accessed on 15 March 2010.

Siegrist, S., Staub, D.; Pfiffner, L. and Mäder, P. 1998. Does organic agriculture reduce soil erodibility? The results of a long-term field study on loess in Switzerland. *Agric. Ecosyst. & Environ.* **69:** 253–264.

Sieling, K., and Kage, H. 2006. N balance as an indicator of N leaching in an oilseed rape-winter wheatwinter barley rotation. *Agric. Ecosys. & Environ.* **115:** 261–269.

Simberloff, D., and Stiling, P. 1996. How risky is biological control. *Ecology* **77:** 1965.

Smil, V. 2008. *Energy in nature and society*. MIT Press, Cambridge, MA.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., et al. 2008. Greenhouse gas mitigation in agriculture. *Phil. Trans. B* **363:** 789–813.

Smolik, J. D., Dobbs, T. L., and Rickerl, D. H. 1995. The relative sustainability of alternative, conventional and reduced-till farming system. *Am. J.Alternative Agric.* **10:** 25–35.

Sommaggio, D., Paoletti, M. G. and Ragusa, S. 1995. Effects of microhabitat conditions, nutrients and predators on the abundance of herbivores on stinging nettles (*Urtica dioica* L.). *Acta Oecologica* **16:** 671–686.

Stalenga, J., and Kawalec, A. 2008. Emission of greenhouse gases and soil organic matter balance in different farming systems. *Int. Agrophysics.* **22:** 287–290.

Stanhill, G. 1986. Water use efficiency. *Adv. Agron.* **39:** 53–85.

Stanhill, G. 1990. The comparative productivity of organic agriculture. *Agric. Ecosyst. & Environ.* **30:** 1–26.

Staley, J. T., Stewart-Jones, A., Pope, T. W., Wright, D. J., Leather, R. S., Hadley, P., Rossiter, J. T., van Emden, H. F., and Poppy, G. M. 2010. Varying responses of insect herbivores to altered plant chemistry under organic and conventional treatments. *Proceedings of the Royal Society B* **277:** 779–786.

Steinhart, J. S., and Steinhart, C. E. 1974. Energy use in the U.S. food system. *Science* **184:** 307–316.

Stockdale, E. A., Lampkin, N. H., Hovi, M., Keatinge, R., Lennartsson, E. K. M., Macdonald, D. W., Padel, S., Tattersall, F. H., Wolfe, M. S., and Watson, C. A. 2001. Agronomic and environmental implications for organic farming systems. *Advances in Agronomy* **70:** 261–327.

Stölze, M., Piorr, A., Häring, A., and Dabbert, S. 2000. The environmental impact of organic farming in Europe. **In:** *Organic Farming in Europe: Economics and Policy*. University of Hohenheim: Hohenheim, Germany. http://orgprints.org/2366/02/Volume6.pdf Accessed 23 November 2009.

Subak, S. 1999. Global environmental costs of beef production. *Ecol. Econ.* **30:** 79–91.

Suh, S., Lenzen, M., et al. 2004. System boundary selection in life-cycle inventories using hybrid approaches. *Environ. Sci. Technol.* **38:** 657–664.

Sullivan, P. 2002. *Drought Resistant Soil*. ATTRA, National Center for Appropriate Technology USDA. http://attra.ncat.org/attra-pub/PDF/drought.pdf Accessed 24 November 2009.

Teasdale, J. R., Coffman, C. B., and Mangum, R. W. 2007. Potential long–term benefits of no–tillage and organic cropping systems for grain production and soil improvement. *Agron. J.* **99:** 1297–1305.

Teasdale, J. R., Rosecrance, R. C., Coffman, C. B., Starr, J. L., Paltineanu, I. C., Lu, Y. C., and Watkins, B. K. 2000. Performance of reduced-tillage cropping systems for sustainable grain production in Maryland. *Am. J. Alternative Agric.* **15**:79–87.

Thies, C., Roschewitz, I., and Tscharntke, T. 2005. Landscape context of cereal aphid-parasitoid interactions. *Proc. R. Soc. Lond. B* **272:** 203–210.

Thies, C., Steffan-Dewenter, I., and Tscharntke, T. 2003. Effects of landscape context on herbivory and parasitism at different spatial scales. *Oikos* **101:** 18–25.

Thies, C., and Tscharntke, T. 1999. Landscape structure and biological control in agroecosystems. *Science* **285:** 893–895.

Thomas, M. B., and Reid, A. M. 2007. Are exotic natural enemies an effective way of controlling invasive plants? *Trends in Ecology and Evolution* **22:** 447–453.

Thomassen, M. A., van Calker, K. J., Smits, M.C.J., Iepema G. L., and de Boer, I.J.M. 2008. Life cycle assessment of conventional and organic milk production in the Netherlands. *Agric. Syst.* **96:** 95–107.

Tilman, D. 1998. The greening of the green revolution. *Nature* **396:** 211–212.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. 2002. Agricultural sustainability and intensive production practices. *Nature* **418:** 671–677.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D., and Swackhamer, D. 2001. Forecasting agriculturally driven global environmental change. *Science* **292:** 281–284.

Trewavas, A. 2001. Urban myths of organic farming. *Nature* **410:** 409–410.

Trewavas, A. 2004. A critical assessment of organic farming-and food assertions with particular respect to the UK and the potential environmental benefits of no-till agriculture. *Crop Prot.* **23:** 757–781.

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., and Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity—ecosystem service management. *Ecology Letters* **8:** 857–874.

Tu, T., Louws, F. J., Creamer, N. G., Mueller, J. P., Brownie, C., Fager, K., Bell, M., and Hu, S. 2006. Responses of soil microbial biomass and N availability to transition strategies from conventional to organic farming systems. *Agric. Ecosyst. & Environ.* **113:** 206–215.

Vandermeer, J., Perfecto, I., and Philpott, S. 2010. Ecological complexity and pest control in organic coffee production: Uncovering an autonomous ecosystem service. *BioScience* **60:** 527–537.

van Elsen, T. 2000. Species diversity as a task for organic agriculture in Europe. *Agric. Ecosyst. & Environ.* **77:** 101–109.

van Veluw, K. 2006. Voice from the other side: A Ghanaian view on organic. **In:** *Organic Agriculture. A Global Perspective*, pp. 351–359. Kristiansen, P., Taji, A., and Reganold, J. Eds., CSIRO Publishing, Collingwood, Australia.

Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E., Johnes, P. J., et al. 2009. Nutrient imbalances in agricultural development. *Science* **324:** 1519–1520.

Vogl, C. R., Kilcher, L., and Schmidt, H. 2005. Are standards and regulations of organic farming moving a way from small farmers' knowledge? *J. Sustain. Agric.* **26:** 5–25.

USDA (United States Department of Agriculture). 2007. Agricultural Statistics. U.S. Department of Agriculture, Washington, DC.

USDA (United States Department of Agriculture). 2010a. Census of agriculture. Organic Production Survey (2008). United States Department of Agriculture. http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Organics/ORGANICS.pdf Accessed on 20 July 2010.

USDA (United States Department of Agriculture). 2010b. Energy use in the U.S. food system. http://www.ers.usda.gov/Publications/ERR94/ERR94_ReportSummary.pdf Accessed on 20 May 2010.

U.S. EPA (United States Environmental Protection Agency). 2010. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2008. April 2010, U.S. EPA # 430-R-10-006. http://epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_ExecutiveSummary.pdf Accessed on 14 May 2010.

Walden, H., Gliessman, S., and Buchananb, M. 1998. Agroecosystem responses to organic and conventional management practices. *Agric. Syst.* **51:** 65–75.

Weibòò, A. C., Östamn, Ö., and Granqvist, Å. 2003. Species richness in agroecosystems: The effect of landscape, habitat and farm management. *Biodiversity and Conservation* **12:** 1335–1355.

Wells, C. 2001. Total energy indicators of agricultural sustainability: Dairy farming case study. Final report. Prepared for Ministry of Agriculture and Forestry by University of Otago, Dunedin. http://www.maf.govt.nz/mafnet/publications/techpapers/techpaper0103-dairy-farming-case-study.pdf Accessed on 20 July 2010.

Westerman, P. S., Wes, J. S., Kropff, M. J., and van der Werf, W. 2003. Annual losses of weed seeds due to predation in organic cereal fields. *J. Applied Ecol.* **40:** 824–836.

Wickramasinghe, L., Harris S., Jones G., and Vaughan, N. 2004. Abundance and species richness of nocturnal insects on organic and conventional farms: Effects of agricultural intensification on bat foraging. *Conserv. Biol.* **18**:1–10.

Willer, H. 2011. The World of Organic Agriculture 2011: Summary. **In:** *The World of Organic Agriculture. Statistics and Emerging Trends 2011*. pp. 26–32. Willer, H. and Kilcher, L. (Eds.) IFOAM, Bonn, & FiBL, Frick. Internet http://www.organic-world.net/fileadmin/documents/yearbook/2011/world-of-organic-agriculture-2011-page-1-34.pdf Accessed on 23 February 2011.

Willer, H., and Yussefi, M. (Eds.). 2006. The World of organic agriculture: Statistics and emerging trends. International Federation of Organic Agriculture Movements (IFOAM), Bonn Germany & Research Institute of Organic Agriculture FiBL, Frick, SwitzerlandSOEL-Survey 2006. Internet http://www.soel.de/inhalte/publikationen/s/s_74_08.pdf. Accessed on February 24, 2008.

Williams, A. 2007. Comparative study of cut roses for the British market produced in Kenya and the Netherlands. http://www.fairflowers.de/fileadmin/flp.de/Redaktion/Dokumente/Studien/Comparative_Study_of_Cut_Roses_Feb_2007.pdf Accessed on 20 July 2010.

Williams, A. G., Audsley, A., and Sandars, D. L. 2006. Energy and environmental burdens of organic and non-organic agriculture and horticulture. *Aspects of Applied Biology* **79:** 19–23. http://orgprints.org/10162/1/Energy_and_environmental_burdens_of_organic_and_non-organic_agriculture_and_horticulture.pdf Accessed 20 May 2010.

Wilson, E.O. (Ed.). 1988. *Biodiversity.* National Academy Press. Available on online at http://www.nap.edu/catalog.php?record_id=989

Wojtkowski, P. 2006. *Introduction to Agroecology: Principles and Practices*. Island Press, Washington D.C.

Wood, R., Lenzen, M., Dey, C., and Lundie, S. 2006. A comparative study of some environmental impacts of conventional and organic farming in Australia. *Agric. Syst.* **89:** 324–348.

Wu, J. Y., and Sardo, V. 2010. Sustainable versus organic agriculture. **In:** *Sociology, Organic Farming, Climate Change and Soil Science.* pp. 41–76. Lichtfouse, E., Ed., Springer, Dordrecht.

Yunus, M. 2009. *Creating a World Without Poverty: Social Business and the Future of Capitalism*. PublicAffairs Cambridge, MA.

Zhu, Y., Chen, H., Fan, J., Wang, Y., et al. 2000. Genetic diversity and disease control in rice. *Nature* **406:** 718–722.

Critical Reviews in Plant Sciences, 30:125–176, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554358

An Heuristic Framework for Identifying Multiple Ways of Supporting the Conservation and Use of Traditional Crop Varieties within the Agricultural Production System

Devra I. Jarvis,[1] Toby Hodgkin,[1] Bhuwon R. Sthapit,[2] Carlo Fadda,[1] and Isabel Lopez-Noriega[1]
[1]*Bioversity International, Maccarese, Rome, 00057 Italy*
[2]*Bioversity International Sub-Regional Office for Asia, Pacific, and Oceania, New Dehli, India*

Table of Contents

Address correspondence to Devra I. Jarvis, Bioversity International, Maccarese, Rome, 00057 Italy. E-mail: d.jarvis@cgiar.org

Referee: Prof. Louise E. Jackson, Chair, Environmental Plant Sciences, Department of Land, Air and Water Resources, University of California Davis, USA.

This paper reviews and discusses how studies on (i) on-farm diversity assessment, (ii) access to diversity and information, (iii) extent of use of available materials and information, and (iv) benefits obtained by the farmer or farming community from their use of local crop diversity, are necessary to identify the different ways of supporting farmers and farming communities in the maintenance of traditional varieties and crop genetic diversity within their production systems. Throughout this paper two key themes are emphasized. First, any description or analysis within the four main areas (assessment, access, use and benefit) can, and most probably will, lead to a number of different actions. Second, the decision to implement a particular action, and therefore its success, will depend on farmers and the farming community having the knowledge and leadership capacity to evaluate the benefits that this action will have for them. This in turn emphasizes the importance of activities (whether by local, national and international organizations and agencies) of strengthening local institutions so as to enable farmers to take a greater role in the management of their resources.

Keywords adaptability, agroecosystem resilience, collective action, biodiversity, community management, farmer selection, genetic diversity, incentives, local institutions, participatory breeding, seed systems

I. INTRODUCTION

The last two decades have provided substantial evidence that significant crop genetic diversity continues to be maintained in farmers' fields in the form of traditional varieties (Bellon *et al*., 1997; Brush, 1995; 2004; Jarvis *et al*., 2004, 2008; Bezancon *et al*., 2009; Kebebew *et al*., 2001; Guzman *et al*., 2005; Bisht *et al*., 2007; FAO, 2010). This diversity constitutes an important element for the livelihood strategies of these farmers. Traditional crop varieties are used because of their adaptation to marginal or specific agricultural ecosystems (Barry *et al*., 2007), heterogeneous environments (Bisht *et al*., 2007), rainfall variability, variable soil types (Bellon and Taylor, 1993; Duc *et al*., 2010) and as insurance against environmental risk (Sawadogo, 2005; Bhandari, 2009), to meet changing market demands (Smale, 2006; Vandermeer, 1995; Brush and Meng, 1998; Gauchan and Smale, 2007), for pest and disease management (Thurston *et al*., 1999; Zhu *et al*., 2000; Trutmann *et al*., 1996; Finckh *et al*. 2003; Jarvis *et al*., 2007a), because of post harvest characteristics (Tsehaye *et al*., 2006; Teshome *et al*., 1999, Latournerie-Moreno *et al*., 2006), distance to market, adult labor availablity and other social and economic characteristics of the household (Gauchan *et al*., 2005; Fu *et al*., 2006; Benin *et al*., 2006; Van Dusen, 2006; Bela *et al*., 2006), and cultural and religious needs (Rana *et al*., 2008; Nabban, 1989; Tuxill *et al*., 2009). They may be kept for their dietary or nutritional value (Johns and Sthapit, 2004; Belanger *et al*., 2008), taste (Sthapit *et al*., 2008a) or for the price premiums they attract because of high-quality traditional properties, which compensate for lower yields (Smale *et al*., 2004). A diversity of traditional varieties within the production system can enable the farmers' crop populations to better adapt and evolve to changing environmental and economic selection pressures, through increasing the farmers' option value (Evenson *et al*., 1998; Gollin and Evenson, 1998; Smale *et al*., 2004; Smale, 2006; Swanson, 1998; Brush, 2004; Kontoleon *et al*., 2007; Pascual and Perrings, 2007; Aguilar-Støen *et al*., 2009), and by widening the genetic base of the crop population (Scarcelli *et al*., 2006; Barnaud *et al*., 2008; Sagnard *et al*., 2008; Carpenter *et al*., 2006; Elmqvist *et al*., 2003; Jackson *et al*., 2007; 2010; Bezançon, *et al*., 2009). The utility of crop varietal diversity within the production system also lies in its potential to provide ecosystem services (Hajjar *et al*., 2008; Ceroni *et al*., 2007; IAASTD, 2009), such as the regulation and control of pest and diseases (Finckh and Wolfe, 2006; Abate *et al*., 2000; Garret and Mundt, 1999; Zhu *et al*., 2000; Strange and Schott, 2005), sustain pollinator diversity (Richards, 2001; Kremen *et al*., 2002), and support below-ground biodiversity and soil health (Swift *et al*., 2004; Brown *et al*., 2007). This can in turn reduce the financial and health risks of high levels of agricultural inputs, such as fertilizer and pesticides to small-scale farmers and the environment (Tilman *et al*., 2001; Mosely *et al*., 2010). This diversity maintained both by farmers *in situ* and by genebanks *ex situ*, continues to be fundamental in trying to achieve global food security (Frankel *et al*., 1995; Gollin and Smale, 1999; Gepts, 2006; Jarvis *et al*., 2007b).

The continuing maintenance of traditional varieties is largely undertaken by poor, small-scale farmers, and is often associated with poverty (Keleman *et al*., 2009; Kontoleon *et al*., 2009; IAASTD, 2009). In these areas, diversity of traditional crop varieties is one of the few options that farmers have to meet their livelihood needs (Sawadogo *et al*., 2005). As long as farmers themselves find it in their best interest to grow genetically diverse traditional varieties of crops, both famers and society as a whole will benefit at no extra cost to either party (Smale *et al*., 2001; Dusen *et al*., 2007). In areas where genetic diversity is significant, but farmers have few market or non-market incentives to maintain it, different public activities will be necessary to help support the conservation of this valuable resource (Smale, 2006; Bellon, 2004).

Although it was widely assumed for many years during the 1970s and 1980s that traditional varieties would be rapidly and completely replaced by modern varieties (Frankel and Soule, 1981), this has not been the case in many production systems. Traditional crop varieties still meet the needs of the farmers and communities where they occur. Indeed, recent studies suggest that one of the responses of poor rural communities to climate change is to increase the use of traditional materials in their production systems (Bezançon *et al*., 2009; Platform for Agrobiodiversity Research, 2010). Their continued maintenance *in situ* also meets a wider social need for evolving and adapted materials to meet changing production needs and challenges. Given the continuing importance to the farmers who grow them, there are good reasons to embed the continued use of traditional varieties into development and improvement strategies designed to improve the well-being of some of the world's poorest communities. A part of this will involve the implementation of appropriate different public activities that can support their maintenance and use.

Over the last few decades, a range of actions or practices has become available to help farmers and farming communities continue to benefit from the maintenance and use of local crop genetic diversity in their production systems (Friis-Hansen and Sthapit, 2000; CIP/UPWARD, 2003; Sthapit *et al*., 2006a; Jarvis and Hodgkin, 2008; Lipper *et al*., 2010; Kontoleon *et al*., 2009) (Table 1).

Most actions are small in scale and site and crop specific, resulting from a local evaluation of farmers' constraints to their current use of local crop genetic resources. Along with the advancement of these actions has been the development of tools and methods to work out which action would be most relevant for a specific situation. There has also been an emphasis on the need to understand the different situations and circumstances of different communities with respect to different crops before deciding on an approach to use.

Although the actions that can support the maintenance and use of traditional varieties are often apparently site, culture or crop specific and varied, we suggest that an overall framework can be usefully created to help conservation and development workers and communities discern which action will most likely be the most relevant in different situations. This framework, a kind of heuristic device, is based on categorizing into four main groups the issues or constraints that farmers face, which may decrease their ability to benefit from the conservation and use of crop genetic resources within their agricultural production systems: (1) the lack of sufficient diversity of traditional crop varieties within the production system; (2) the lack of access by farmers to available diversity, (3) the limitations in information on and the performance of varieties available in key aspects, and, (4) the inability of farmers and communities to realize the true value of the materials they manage and use. Figure 1 contains a descriptive diagram of the relations within this heuristic device and connects the outcome of analyses of the different types of information to an array of potential actions (Table 1).

Based on a review of literature, this paper discusses how studies on (i) on-farm diversity assessment, (ii) access to diversity and information, (iii) extent of the use of available materials and information, and (iv) benefits obtained by the farmer or farming community from their use of local crop diversity, are necessary to identify the different ways to support farmers and farming communities in the maintenance of crop genetic diversity within their production systems. Throughout this paper two key themes are emphasized. First, any description or analysis within the four main groups can, and most probably will, lead to a number of different actions. Second, the decision to implement a particular action, and therefore its success, will depend on the farmer and the farming community having the knowledge, institutions and leadership capacity to evaluate the benefits that this action will have for them. This in turn promotes an emphasis on the importance of strengthening local institutions to enable farmers to take a greater role in the management of their resources.

II. ON-FARM DIVERSITY ASSESSMENT

The assessment of diversity provides the necessary description of the extent and distribution of genetic diversity of traditional varieties, and of the way in which that diversity is partitioned within and among varieties at household and community levels. It allows exploration of the relation of the observed diversity to factors such as ecology, gender or poverty. Description in terms of variety names and the traits farmers use to describe their varieties is important for understanding how well their materials are adapted to the farmers' environments and preferences, as well as the farmers' perspectives of diversity distribution. Genetics, particularly molecular genetics, provides further information on patterns of diversity distribution and allows the investigation of the relation of observed diversity with environmental, social and cultural factors, providing a means to reconcile classification schemes using farmers' varietal names with genetic distinctiveness. It also helps determine whether there is a wide enough genetic base for future improvement of the *in situ* materials, or whether there is sufficient diversity to provide system resilience (Figure 1: $1a$, $1b$).

A. Understanding Farmers' Diversity Units and Estimating the Diversity of Traditional Varieties

Diversity within the agricultural production system can be assessed at different levels: within and among households, villages, communities and countries. Many studies are now available which describe the amount and distribution of genetic diversity of individual crops in farmers' fields, at different scales, using a wide range of methods. These studies range from counting the names of varieties to biochemical and molecular studies which assess allelic richness and heterozygosity (Berg, 2009; Brown, 2000). Some studies have developed and used indices of diversity or other methods to compare the amount and distribution of diversity within the farmers' production system across sites and crops. Not all production systems have the same amounts of diversity or the same reliance on traditional cultivars (Bajracharya *et al*., 2006; Eyzaguirre and Linares, 2004; Gautam *et al*., 2008). The diversity found within one community may or may not be representative of a much wider geographical area (Chavez *et al*., 2000; Guzman *et al*., 2005).

Many studies have reported the numbers of farmer-named varieties at household and community levels for major crops, including corn (Bellon and Taylor, 1993; Bellon and Brush, 1994; Louette *et al*., 1997), common bean (Martin and Adams, 1987; Voss, 1992), potatoes (Quiros *et al*., 1990; Brush *et al*., 1995; Zimmerer, 2003), sorghum (Tesema *et al*., 1997) and cassava (Boster, 1985; Salick *et al*., 1997; Kizito *et al*., 2007), barley (Kebebew *et al*., 2001; Gupta *et al*., 2003; Banya *et al*.,

TABLE 1

Descriptions and references to actions used to support the conservation and use of traditional crop varieties within agricultural production systems. Numbers and letters in the column, "*Where applicable*," refer to specific constraints outlined in the heuristic framework shown in Figure 1. Actions can be used to overcome multiple constraints.

General category actions (*Note: Actions can be applicable to more than one category)*	Actions	Where the action is applicable to specific constraints outlined in the Heuristic Framework (Figure 1)	Description of Actions	References
Improving availability of materials	Reintroduction of materials from *ex situ* collections	1a, 2a	Local landraces from national gene bank or community gene bank are re-introduced based on ecological adaptive characteristics and human preferences	De *et al*., 2000; Arndorfer *et al*., 2009; Iriarate *et al*., 2000 http://www.actahort.org/books/817/817_35.htm; Feyissa, 2000; Feyissa *et al*., 2005; UNORCAC, 2008
	Reintroduction of materials from similar environments	1a, 1b, 2a	Local varieties collected from farmers from similar environments are integrated into informal seed system	Maurya *et al*., 1988; Sismanto, 2003; Joshi and Sthapit, 1990; Louette *et al*., 1997, Zimmerer 2003, Valdivia 2005, Chavez-Servia *et al*., 2000, Belqadi, 2003; Sthapit and Rao, 2009; Bhandari, 2009
	Seed Cooperative for collection and distribution and multiplication of seeds	1b, 2a, 2b, 2c, 2d, 4c	Community seed production groups; Participatory Seed Exchange (PSE); Grassroots seed savers networks; Cooperative is formed to market successful varieties or to establish seed enterprises for farmers to have a clean source of seeds.	Shrestha, Pitamber *et al*., 2010; Janssen *et al*., 1992 (Colombia), Musa 1998, Tripp 2006, Kabambe *et al*., 2008; Ramirez *et al*., 2009; Thijssen *et al*., 2008; de Boef *et al*., 2010
	Community Seed Bank	1b, 2a, 2b, 2c, 2d 3a,4b, 4c	To improve access to locally adapted varieties, local crops germplasm is collected together with associated information and knowledge, stored, regenerated or multiplied as needed and distributed to fulfill seed demands of farmers.	Shrestha P *et al*., 2006; 2010; Maharjan *et al*., 2010a; Balma *et al*., 2005; Bertuso *et al*., 2000; Lewis and Mulvany, 1997; Ramprasad, 2009; Sateesh, 2000; Feyissa, 2000; Mazhar, 2000; Mujaju, *et al*., 2003; Bertuso *et al*., 2000; Almekinders *et al*., 2007; Garforth *et al*., 2005; Mujaju and Chakauya, 2008; Bezabiha, 2008; Lewis and Mulvany, 1997; Poudel *et al*., 2005; Thijssen *et al*., 2008; Swaminathan, 2001; FAO 2006a
	Community Gene bank	1a, 1b, 2a, 2d	Local crop germplasm accessions are deposited by farmers for short term storage, and later multiplication and regeneration by other groups.	Kesavan and Swaminathan 2008; Ramirez *et al*., 2009; Swaminathan, 2001; Engels *et al*., 2008

Community managed nurseries	1b, 2a, 2b, 2c, 2d 3a,4b, 4c	Community nurseries allow growers to access both mother plants (scion and rootstocks) and the associated information. They also are a place for farmers to learn about better nursery management practices.	Oyedele *et al*., 2009; Shalpykov, 2008; Kerimova, 2008; Djavakyants, 2010
Diversity field flora	1b, 2a, 2b, 2c, 2d, 3a, 3b, 3c, 4b, 4c	In order to supply an evolving diversified gene pool through exchange and selection to allow the continued adaptation to changing conditions through the informal seed system, farmers' groups in low heritability environments test both improved and local cultivars and the selected cultivars are multiplied and disseminated within and outside the groups. The approach can be used to meet preferences of women and men farmers that often different.	BUCAP, 2002; Smolders & Caballeda, 2006, Bioversity International, 2009; Jackson *et al*., 2010; Huvio and Sidibe, 2003; Grum *et al*., 2003; Bhandari, 2009
Diversity Kit	1b, 2a, 2b, 2c, 2d 3a,,4b, 4c	Diversity kit is a set of small quantity of different seeds made available to farmers to enhance their access to a wider range of local varieties. Seeds are harvested from diversity blocks, research farms or farmer's fields and distributed among the farmers.	Sthapit *et al*., 2006d; Sthapit *et al*., 2008b; Joshi and Sthapit, 1990; Sperling *et al*., 2001, Almekinders *et al*., 2006, Halewood *et al*., 2007
Diversity Fairs	1b, 2a, 2b, 2c, 2d 3a,4b, 4c	Diversity fairs aim not only at promoting the exchange of knowledge and germplasm between farmers, but they are also organized to explore diversity-rich areas and to recognize communities as custodians of traditional knowledge and biodiversity. Farmers from different communities are brought together to exhibit a range of traditional varieties and the farmer's knowledge of their varieties. Diversity fairs are organized differently to fit the culture of a specific community.	Tapia, and Rosa 1993;Sthapit, 1998; Rijal *et al*., 2000; Sthapit *et al*., 2003a; Rusike *et al*., 2003; Guerette *et al*., (undated); Sperling *et al*.,. 2008; Adhikari 2006b; UNORCAC, 2008; CIP/UPWARD, 2003; Hardon, and de Boef, 1993; Satheesh, 2000
Seed vouchers	1a,1b,2a,2b,3c,2d,	Seed vouchers are coupons or certificates with a guaranteed cash value that can be exchanged for seed from approved sellers. Seed sellers can then redeem their vouchers for cash from the issuing agency.	CRS, ICRISAT and ODI. 2002; Makokha *et al*., 2004; Remington *et al*., 2002; van der Steeg *et al*., 2004; Alexander *et al*., 2004

(Continued on next page)

TABLE 1

Descriptions and references to actions used to support the conservation and use of traditional crop varieties within agricultural production systems. Numbers and letters in the column, “*Where applicable*,” refer to specific constraints outlined in the heuristic framework shown in Figure 1. Actions can be used to overcome multiple constraints. *(Continued)*

General category actions (*Note: Actions can be applicable to more than one category)*	Actions	Where the action is applicable to specific constraints outlined in the Heuristic Framework (Figure 1)	Description of Actions	References
	Reduce transportation costs of traditional variety material closer to farmer communities	2a,2b,2c	In order to reduce transportation costs, NGO, Community based organizations, extension and other development organizations assess transportation costs as a regular annual program. Private fruit processor such as Gallas provides transportation cost of mango and other fruits directly to factories rather than middlemen so they can pay higher price to farmers.	Phiri *et al*., 2004
	Cross site visits for farmers and local extension workers	1a, 2a, 2b,3a, 3c	Cross-site visits aim at exposing each participating farmer to good practices adopted by another community and to demonstrate these practices to five farmers in their site. Participating farmers must present the learning from the visit to rest of the farmers immediately after the completion of the exposure visit.	LI-BIRD, 2005; Jarvis *et al*., 2000; UNORCAC, 2008; Nassif and Birouk, 2002; Nassif, 2002; Jarvis *et al*., 2004
	Microfinance or credit schemes to enable purchase of local materials	2a,2b,2c	Micro credit facilities provided by national banks, foundations, and international and national NGOs.	Kesavan and Swaminathan, 2008, UNORCAC, 2008
Improving information and availablity of information	On-farm Diversity blocks	1b, 2a, 2b, 2c, 2d 3a, 4c	A diversity block is an experimental block of farmers’ varieties for research and development purposes managed by local institutions. A group of knowledgeable farmers is invited to observe the diversity block during cultivation. The block can also be used for the multiplication of planting materials, following cultivation of rare germplasm in the block.	Sthapit *et al*., 2006c, 2008c

Field or Laboratory trials comparing traditional and modern varieties	1b, 2a, 2b, 2c, 2d 3a,	Comparing traditional and modern varieties in field and laboratory trials gives quantitative differences of productive and adaptive characteristics under farmers' conditions. It also helps to demystify technology for farmers; Various methods such as Farmer Field Trials (FFT), PVS and Mother-Baby Trials are developed for this purpose.	Bouhassan *et al*., 2003a; Tushmereirwe, 1996; Bertuso *et al*., 2005; Rijal 2009; McGuire *et al*., 2002; Celis-Velazquez *et al*., 2008; Kennedy and Burlingame, 2003; Cazarez-Sanchez, 2004; Cazarez-Sanchez and Duch-Gary, 2004; Demissie & Bjørnstad, 2004; Trutmann *et al*., 1993; Karamura and Karamura 1995; Finckh *et al*., 2000; Joshi and Witcombe, 1996
Community Biodiversity Registries	3a, 3d, 4a, 4b, 4c	Community Biodiversity Register (CBR) is a record, kept in a register by community members, of the genetic resources in a community, including information on their custodians, passport data, agroecology, and cultural and use values. The method is to document traditional knowledge on genetic resources and provide defensive protection from bioprospecting.	Subedi, *et al*., 2005; Aboagye, 2005; Sthapit and Quek, 2005; Anil Kumar *et al*., 2003; Ruis, 2009
Literacy training particularly for poor and vulnerable groups		Literacy training enables farmers, particularly women, to have more access and control over their resources, and to have access to new options.	FAO, 2005; Jarvis *et al*., 2004; Kesavan and Swaminathan 2008
Variety information data bases made in farmer friendly formats	3a, 3d, 4a, 4b, 4c	Variety and plot data linked to GIS systems that are in farmer friendly formats allow farmers to see visually the distribution of different varieties in their community. They may also be used to map soil types and disease infestation to help farmers to make decisions on which varieties would be suitable for different agroecological conditions on their farmers.	Kesavan and Swaminathan, 2008
Setting up information systems and internet connections for farmer access to information	2a, 2b, 2d, 3a, 3d, 4a, 4b, 4c	Knowledge empowerment can be obtained by taking advantage of the new information and communication technology and providing internet connections. Using solar power where electricity is not continuous or available and through cell phone connections, a wire-wireless hybrid technology can be developed.	Kesavan and Swaminathan, 2008; Munyua *et al*., 2009; Lightfoot *et al*., 2008; Kenny, 2000

(Continued on next page)

TABLE 1
Descriptions and references to actions used to support the conservation and use of traditional crop varieties within agricultural production systems. Numbers and letters in the column, "*Where applicable*," refer to specific constraints outlined in the heuristic framework shown in Figure 1. Actions can be used to overcome multiple constraints. *(Continued)*

General category actions (*Note: Actions can be applicable to more than one category)*	Actions	Where the action is applicable to specific constraints outlined in the Heuristic Framework (Figure 1)	Description of Actions	References
	Small weather stations that can be linked to internet sites	3a,3c,4b,4c	In the developed world networks of weather stations in farming regions are becoming the norm. Farmers tap into these for real-time weather data and in some cases, use models for crop growth development and pest/disease forecasts. In some cases, farmers have their own weather stations. A relatively inexpensive weather station can be purchased for a farming community and added to a free weather networks such as Wunderground Weather, the network that makes local data available to others in a region or globally.	T. Murray personal comm, 2010; http://www.wunderground.com/weatherstation/index.asp#hardware
	Rural radio program that includes talks on the importance of crop biodiversity	3a,3d, 4a,4b,4c	Radio broadcasting is one of the quickest and more powerful means for providing information and raising awareness of people living in rural and semi-urban areas. Rural radio not only disseminates information to stakeholders but also provides forum for sharing opinions on various issues related to the conservation and management of biodiversity to a larger audience. Some CBOs have their own farmer-managed station to disseminate information and knowledge useful to the community.	Shah *et al*., 2009; Baral *et al*., 2006; Ballantyne 2009; Balma *et al*., 2005

	Drama, music and poetry traveling shows that have crop biodiversity as the theme	3a,3d, 4a,4b,4c	Often traditional knowledge is embedded in folk songs, poem and folk tales as they reflect social and cultural values in the community. The information or message passed on through this medium is easily acknowledged by the people and acts as an effective tool to sensitize the communities in developing countries when songs, poems and local theater as also a mode of entertainment.	Sthapit, 1999; Rijal *et al*., 2000; Dewan *et al*., 2006; Satheesh, 2000
	Painting and art competitions that reward farmer groups for knowledge and descriptions of agricultural diversity	3a,3d, 4a,4b,4c	A contest takes place among participants from the villages belonging to different communities, or different schools. Prizes decided with the communities are give for the painting or art that best depicts the ideas of conservation and use of traditional varieties.	Tapia, 2000; Sunwar *et al*., 2005
Improving traditional variety matierals and their management	Participatory crop improvement (Grassroots breeding; Participatory Plant Breeding (PPB); Participatory Varietal Selection (PVS))	2d, 3a, 3b, 3c, 3d, 4a,4b,4c	The value of local crop diversity can be enhanced in three broad ways: 1) simple trait selection from existing diversity of local population (e.g. grassroots breeding), 2) selection of fixed (stable variety) for target environment (PVS), and 3) cross local parent with exotic variety to remove the bad traits from local diversity (PPB). Locally based, participatory plant breeding exploits the diversity of local germplasm to produce cultivars that are superior in marginal environments compared to the products of formal, centralized programs, but at the same time continue to have a broad genetic base. The most key elements of this exercise are setting breeding goal by the farming community; plant breeders assist them to improve local materials under thier target environments and farmers contribute to the pre- and post-harvest selection.	Witcombe *et al*., 1996; 2005; 2006; Sthapit *et al*, 1996; Sthapit and Jarvis, 1999; Sthapit *et al*., 2000; 2003b; Joshi *et al*., 2000; Joshi *et al*., 2001; 2002; Ceccarelli and Grando, 2007; Witcombe *et al*., 2005; Gyawali *et al*., 2006a; 2006b; 2007; Gibson, 2009; Chiffoleau, & Desclaux, 2006;Danial *et al*., 2007; Almekinders *et al*., 2006; Ortiz *et al*., 2009; Lacy *et al*., 2006; Valdivia Bernal *et al*., 2007; Sunwar *et al*., 2007; Belay *et al*., 2006, 2009; Ceccareli *et al*., 2009; Halewood *et al*., 2007;

(Continued on next page)

TABLE 1

Descriptions and references to actions used to support the conservation and use of traditional crop varieties within agricultural production systems. Numbers and letters in the column, “*Where applicable,*” refer to specific constraints outlined in the heuristic framework shown in Figure 1. Actions can be used to overcome multiple constraints. *(Continued)*

General category actions (*Note: Actions can be applicable to more than one category)*	Actions	Where the action is applicable to specific constraints outlined in the Heuristic Framework (Figure 1)	Description of Actions	References
	Using genomics to improve *in situ* crop populations	2d,3 b, 3c,3d, 4a, 4b	Breeding desirable traits into materials adapted to abiotic and biotic conditions in a specific environment; backcross breeding of specific traits into locally adapted material	Witcombe *et al*., 2008; Steele *et al*., 2004; 2007; Barr, 2010
	Changing the formal breeding institutions to increase the use of farmer selection materials and traditional varieties in their programs	2d, 3a, 3b, 3c, 3d, 4a,4b,4c	National resistance breeding procedures integrate farmer selection practices and local material and participatory breeding practices to improve other production and quality traits of locally-resistant varieties as well as the resistance of locally adapted non-resistant varieties.	Mendum and Glenna 2010; Finckh 2008; Gibson, 2009; Mgonja *et al*., 2005; FAO 2010
	Planting of intra-specific mixtures to reduce pests an diseases	2d, 3a, 3b, 3c, 3d, 4a,4b,4c	Traditionally, farmers use diversity for any adversity by employing mixed farming, intercropping and varietal mixture within the species. Varietal mixtures or sets of varieties should have with non-uniform resistance and a lower probability that migrations of new pathogens or mutations of existing pathogens will damage the crop. Mixtures are based on the analysis of the resistance background, agronomic character, economic value, local cultivation conditions and farmer preferences.Traditional farming practices suggest that cultivation of a mixture of crop species in the same field through temporal and spatial management may be advantageous in boosting yields and stability and preventing disease.	Pradhanag and Sthapit, 1995; Finckh, 2008; Finckh, and Wolfe, 2006; Di Falco and Perrings 2006; Zhu *et al*., 2000; Thinlay *et al*., 2000; Finckh, 2003; Trutmann and Pyndji, 1994; Ghaoti *et al*., 2005, Li *et al*., 2010; Benton *et al*., 2003; Willey, 1997

	Improve seed storage facilities and methods	3c,3d,4a,4c	Seed storage devices and methods determine the vulnerability of seeds to pests, diseases and physiological deterioration. Some common methods are improving the air tightness of containers or head treatment. Some tested examples combine traditional with modern methods e.g. cow dung ash was combined with air tight storage to increase the seed longevity.	Gepts, 1990; Yupit-Moo, 2002; Latourniere *et al*., 2006; Grum *et al*., 2003a; Wambugu *et al*., 2009; Thamaga-Chitja *et al*., 2004; Beckett *et al*., 2007
	Seed cleaning/ seed treatment	3c,3d,4a,4c	Seed cleaning technology for seed born diseases, normally recommend for certified varieties can be used on traditional varieties to increase yield. This includes supporting farmers for small seed cleaning machines.	Sadiki *et al*., 2002
Improved Processing	Shift retailers to use different processing equipment that can use diversified materials	3c,3d, 4a,4a,4c	Complementary technical solutions will be necessary to integrate the future use of agricultural strategies that include the use of diverse traditional varieties. These may include simple adjustments of planting and harvesting devices to new separation of the harvest products.	Finchk, 2008; Walsh *et al*., 2004
	Training of producers in improved processing techniques; and providing credit to acquire processing equipment	3c,3d, 4a,4a,4c	Training of farmers in improved processing techniques enables farmers to process traditional varieties into improved market products. This can be linked to micro credit to purchase processing equipment.	Giuliani, 2007; Devaux *et al*., 2006; Kontoleon *et al*., 2007
Alternatives and modification to seed certification systems	Plant varieties common knowledge (VCK)	2d, 3a, 3d, 4a, 4b, 4c	‘Common knowledge’ can be defined as having shared information or understanding among members of a specific ‘community’, including a nation, a region, a city, a particular race, an ethnic group, or a professional society, which permits a variety to be precisely defined and distinguished by the members of that particular community.	Prasann *et al*., 2008; Mazhar, 2000

(Continued on next page)

TABLE 1

Descriptions and references to actions used to support the conservation and use of traditional crop varieties within agricultural production systems. Numbers and letters in the column, "*Where applicable,*" refer to specific constraints outlined in the heuristic framework shown in Figure 1. Actions can be used to overcome multiple constraints. *(Continued)*

General category actions (*Note: Actions can be applicable to more than one category)*	Actions	Where the action is applicable to specific constraints outlined in the Heuristic Framework (Figure 1)	Description of Actions	References
	Registration and release of famers' varieties with acceptance of enhanced bulk varieties	2d, 3a, 3d, 4a, 4b, 4c	Following participatory assessment of the enhanced bulk variety in the field together with farmers, mill owners and retailers, a formal seed registration board may establish that a bulk population is phenotypically similar fo agronomic, post-harvest, quality traits and market preferences and can recommend the formal registration and release of the enhanced bulked variety adapted to local conditions.	Joshi *et al*., 1997; Gyawali *et al*., 2007; Bishaw and van Gastel, 2009; Bealy, 2007; Halewood *et al*., 2007
	Geographic Indications	2d, 3a, 3d, 4a, 4b, 4c	A Geographical Indication is a form of protection within the Trade Related Aspects of Intellectual Property Rights (TRIPS) Agreement of the World Trade Organization (WTO). It protects intangible economic assets such as the quality and reputation of a product through market differentiation. It is a tool to maintain multifunctionality in rural landscapes and involve local populations in biodiversity management and conservation by providing incentive for marketing special products.	Ramakrishnappa 2006; Garcia *et al*., 2007; Nagarajan, 2007; Salazar *et al*., 2007; http://www.origin-gi.com/
	Quality declared seed (QDS) - that certify the vendor rather than the seed	2d, 3a, 3d, 4a, 4b, 4c	Small scale farmers are registered to produce seed for local sale. A QDS producer is trained in QDS production of a crop they can decide later to add additional crops or varieties to their seed production at their own risk. The QDS vendors are inspected by authorized seed inspectors at district level	FAO 2006b; Granquist, 2009

Truthfully labeled seed Laws that focus on seed quality rather than seed purity	2d, 3a, 3d, 4a, 4b, 4c	In India, for example, the truthfully labeled seed law has been designed to focus on seed quality rather than varietal purity.	Lipper *et al*., 2010b
Registries of native crops	2d, 3a, 3d, 4a, 4b, 4c	The register indentifies and recognizes the individuals, institutions or communities who maintain, conserve and work on native crops, but does not grant specific rights to those who are applicants to the register. The registry contains the main agronomic, agroecological and taxonomic characteristics of the varieties of native crops. It clearly identifies the origin and diversification centers, and raises awareness through verified technical and scientific official information. It identifies groups of farmers, individuals and institutions that care about conservation and use of agricultural biodiversity and those persons that have been instrumental in ancestral efforts of conservation. It contributes to preventing actions of biopiracy.	Ruis, 2009; Subedi, *et al*., 2005; Aboagye, 2005; Sthapit and Quek, 2005; Anil Kumar *et al*., 2003
Links between intellectual property rights protection and benefit-sharing	4a, 4b, 4c	Some legislations like the Thai Plant Variety Protection Act requires the holders of plant breeders' rights to give part of the benefits arising from the commercialization of the protected varieties to a fund dedicated to on farm conservation of crop diversity. Similarly, at the international level, the multilateral system on access and benefit-sharing of the International Treaty on Plant Genetic Resources for Food and Agriculture creates a benefit-sharing fund for conservation projects where vendors of new plant varieties that are not freely available for research and breeding must put part of the benefits derived from the varieties' commercialization.	Moore and Tymowski, 2005; Gagne and Ratanasatien, *in press*

(Continued on next page)

TABLE 1

Descriptions and references to actions used to support the conservation and use of traditional crop varieties within agricultural production systems. Numbers and letters in the column, "*Where applicable*," refer to specific constraints outlined in the heuristic framework shown in Figure 1. Actions can be used to overcome multiple constraints. *(Continued)*

General category actions (*Note: Actions can be applicable to more than one category)*	Actions	Where the action is applicable to specific constraints outlined in the Heuristic Framework (Figure 1)	Description of Actions	References
	Plant variety protection systems adapted to farmers varieties	3d	Effective *sui generis* systems of farmers' varieties protection can empower individual farmers and farmers communities and prevent misapropriation of farmers' varieties by others.	Leskien and Flitner, 1997; Correa, 2000
Market creation and Market promotion	Market promotion through taxes and subsidies	4a,4b, 4c	Market promotion through taxes for environmental damage and subsidies for environmental friendly practices or for the use of traditional crop varieties within the farmers' production system.	Kruijssen and Mysore, 2007
	Market creation for traditional varieties or products from traditional varieties including niche markets	2d, 3a, 3b,3d,4a,4c	Demand for unusual heirloom or niche market varieties exists among urban residents or other consumers. Niche markets might be for traditional varieties that are "best fit" to particular ecosystems, such as particular traditional varieties shown to grow well on swampy soil or on poor upland soils. Marketing social-cultural aspects of traditional varieties for particular culinary aspects and associated ethnic identity has also been used to create niche markets.	Lee, 2005; Irungu *et al*., 2007; Giuliani, 2007; van Dusen, 2006; Gauchan and Small, 2003; Rana, 2004; Gruere *et al*., 2007; Caviglia and Kahn, 2001; UNORCAC, 2008; de Boef, 2010; Bhandari *et al*., 2006; Bhandari, 2009
	Education and financial support to farmers' groups to develop a marketing strategy	3a, 4a, 4c	Institutions support farmer unions and cooperatives for educating farmers in production and marketing, assisting with price negotiations, collecting land taxes, information sharing.	Kruijssen and Somsri, 2006; Ramirez *et al*., 2009; Caviglia and Kahn, 2001.

Micro credit facilities to set up small businesses particularly for rural men and women	4a, 4b, 4c	Micro-finance and micro-insurance schemes are innovative ways of providing the poor with access to capital and thus a way out of poverty. Micro credit is a small amount of money loaned to a client by a bank or other institution. Micro credit can be offered, often without collateral, to an individual or through group lending. Micro credit schemes can enable farmers, especially women to engage in economic activities and join social networks through which both poverty and social dependency can be overcome.	Kesavan and Swaminathan, 2008; UNORCAC, 2008; Kapila and Mead, 2002; Gine and Yang, 2009; Andersen *et al*., 2008
Advertisement campaigns to improve consumer and retailer awareness of important traits (nutritional, adaptive)	3a,3b, 3c,3d,4a,4b,4c	Marketing nutritional and health (both human and environmental) related information to wider consumers to add value. This includes providing consumers and retailers with information on traditional variety traits.	Johns and Sthapit 2004; Kennedy and Burlingame 2003.
Cook books with traditional recipes; gardening books that promote traditional varieties for particular management practices	3a,3b,3d,4b,4c	Recipes that require traditional varieties; organized synthesized and published; Gardening books that promote traditional varieties for their uses can be useful for raising awareness.	Yucatan cook book; Sthapit *et al*., 2008a; Gruere *et al*., 2007; Ramirez *et al*., 2009
Fair trade price premiums - Eco-labeling (paying the full production value through price premiums)	2d, 3a, 3b, 3c, 3d, 4a, 4c	Fair trade or eco-labeling is a conservation strategy that is market based, in which consumers pay a price premium for a product which is produced on certified farms that are committed to the preservation of biodiversity or fair working conditions; the label of fair trade requires that the buyers agree to: pay a price that covers the production costs and a social premium; make an advance payment; purchase directly from the producer; and establish long-term contracts.	Kitti *et al*., 2009; Perfecto *et al*., 2005; Swallo and Sedjo, 2000; 2002; Renard, 2003

(Continued on next page)

TABLE 1

Descriptions and references to actions used to support the conservation and use of traditional crop varieties within agricultural production systems. Numbers and letters in the column, “*Where applicable*,” refer to specific constraints outlined in the heuristic framework shown in Figure 1. Actions can be used to overcome multiple constraints. *(Continued)*

General category actions (*Note: Actions can be applicable to more than one category)*	Actions	Where the action is applicable to specific constraints outlined in the Heuristic Framework (Figure 1)	Description of Actions	References
Building Partnerships and Trust	Organization of meetings involving market-chain actors to discuss how to enhance market potential.	3a,3b,3c, 4a, 4c	Stakeholder meetings, involving as many as possible of the market chain actors including producers and traders, cultivation experts, NGOs, representative of relevant ministries, and community members to develop ideas for enhancing market potential for traditional varieties.	Giuliani, 2007; Kruijssen *et al*., 2009
	Private and public partnership for the construction of small infrastructure for the production of a better quality product	3a,3b,3c, 4a, 4c	The formulation of producer marketing groups, and micro-enterprise that provides better access to local, national, and international markets for locally grown and processed products.	Giuliani, 2007; Audi *et al*., 2010; Friss-Hansen, 2008; Pretty, 2008; Jarvis, and Ndung’u-Skilton, 2000; Swaminathan, 2003; UNORCAC, 2008
	Strengthened and cooperative extension service that includes farmers, are more demand driven or establishment of new farmer-governed local institutions	1a, 1b, 2a,2b,2c, 2d, 3a, 3b, 3c, 4a, 4b, 4c	Transformation of local government staff and establishment of new farmer-governed local institutions specifically focusing on the management of local varieties; Particularly for poor and marginalized groups.	Triomphe *et al*., 2008; Sthapit *et al*., 2008c; Adhikari *et al*., 2006a; Friis-Hansen *et al*., 2008; Birner and Anderson, 2007; Neuchatel Group, 2007 (http://www.neuchatelinitiative.net/english/index.htm)

Changing norms	Advertising and social campaigns that promote better adapted varieties that reduce need for chemical inputs to change social norms such as nutritional cultural values of food	3a, 3d, 4a, 4b, 4c	Advertsing campaigns to change norms on nutrition and taste, and to reduce chemical inputs for better environmental protection. These campaigns may opt to demonstrate the full cost to the environment and human health of high input fertilizer and pesticide systems and emphasize social obligations to the reduction of pesticides and fertilizer and other harmful practices for the environment.	McGuire, 2008; Meinzen-Dick and Eyzaguirre, 2009; Sthapit *et al*., 2008a
	School biology curriculum include traditional crop varieties as an agricultural resource and ecosystem service	1a, 1b, 3a, 3d, 4a, 4b, 4c	Modification of curriculum content of primary and middle school, and high education institutes to include traditional crop varieties as an agricultural resource and provider of ecosystem services	Ramirez *et al*., 2009; Jarvis *et al*., 2000; Visser and Jarvis, 2000; Bioversity International, 2008
	Gender sensitive response policy	1,2,3,4	Promoting women in decision-making and project management roles, has increased the number of women who are given training opportunities; Women are actively sought after for decision making positions in projects	MEA 2005, Tapia and De la Torre, 1998
Promoting ecological land management practices	Environmentally sensitive areas (ESA) include high agrobiodiversity areas	3a, 3b, 3c, 4b, 4c	Areas oriented to the conservation and sustainable use of native cultivated species by indigenous peoples	Mar 2002; Birol *et al*., 2006; Amend *et al*., 2008
	Agriobiodiversity Zones	3a, 3b, 3c, 4b, 4c	Agricultural zones of important native cultivated germplasm under management of native communities are designated formal legal status	Ruis, 2009; UNORACA, 2008

TABLE 1

Descriptions and references to actions used to support the conservation and use of traditional crop varieties within agricultural production systems. Numbers and letters in the column, “*Where applicable*,” refer to specific constraints outlined in the heuristic framework shown in Figure 1. Actions can be used to overcome multiple constraints. *(Continued)*

General category actions (*Note: Actions can be applicable to more than one category)*	Actions	Where the action is applicable to specific constraints outlined in the Heuristic Framework (Figure 1)	Description of Actions	References
	Agrobiodiversity Ecotourism	3a, 3b, 3c, 4a, 4b, 4c	Agrobiodiversity ecotourism is aimed toward amateur interest in the diversity of cultivated plants and in the cultural practices associated with crop. Agrobiodiversity toursim projects are managed in close partnership with local communities and can involve such activities as farm and market visits, participation in agricultural activities and food preparation, tastings of local foods and beverages and attendance at specific feasts and celebrations	Ramirez, 2001, Ramirez and Williams, 2003; Ramirez *et al*., 2003; UNORACA, 2008
	Organic farming and organic seed breeding with traditional variety used as planting materials	2d, 3a, 3b, 3c, 3d, 4a, 4b, 4c	Utilize traditional varieties in organic farming where traditional varieties are well adapted to local conditions. Organic farmers are obliged to use organically produced seeds and propagating material.	Bela *et al*., 2006
	Investment in agricultural research that includes the use of agricultural biodiversity within the production system	1, 2, 3, 4	Investment in agricultural research and extension has contributed significantly to agricultural growth and rural poverty reduction in rural areas.	MEA, 2005; Fan *et al*., 2007

	Biodiversity included in Environmental Impact Assessment of individual projects, policies and programmes	1, 2, 3, 4	By integrating biodiversity, including agriculture biodiversity, in the legislation on environmental impact assessment, decision-makers can adopt informed decisions with regard to agrobiodiversity conservation and use.	Slootweg *et al*., 2006; Wale, *in press*
Payment schemes for ecosystem services	Payment for Environmental Services (PES)	2d, 3d, 4b, 4c	The real value of agrobiodiversity and its services is not captured by the market because of a failure to internalize external costs. Farmers who provide environmental services are compensated, either by the immediate beneficiary or by the general public. Payment for Environmental Services (PES) schemes permit “capture” of public conservation values at the farmer level, thereby creating incentives for the conservation of agrobiodiversity and supporting poverty alleviation.	Pascual and Perrings, 2007; van Noordwijk, *et al*., 2005; FAO, 2007; Wunder *et al*., 2008
	Linking upstream and downstream communities	2d, 3d, 4b, 4c	An example is an environmental payment system initiated in 2002 in the Rupa Lake area, Nepal. The Rupa Lake Cooperative pays 10% of its income from fishery management to the upstream communities. The realization among the users of the Rupa Lake about the potential role of upstream and downstream communities in management of the lake has led to expansion of members within the cooperative. The 360 membership in the cooperative in 2006 is now more than 600 members.	Pradhan *et al*., 2010
	Sharing of monetary benefits	4a, 4b, 4c	A way of realizing farmers’ rights and support farmers who conserve and generate crop diversity is by sharing the monetary benefits arising from the commercializaiton of new varieties with farmers, in combination with other forms of benefit-sharing. A number of countries have developed legislation on benefit-sharing and some of them refer to traditional farmers as final beneficiaries.	Andersen, 2005

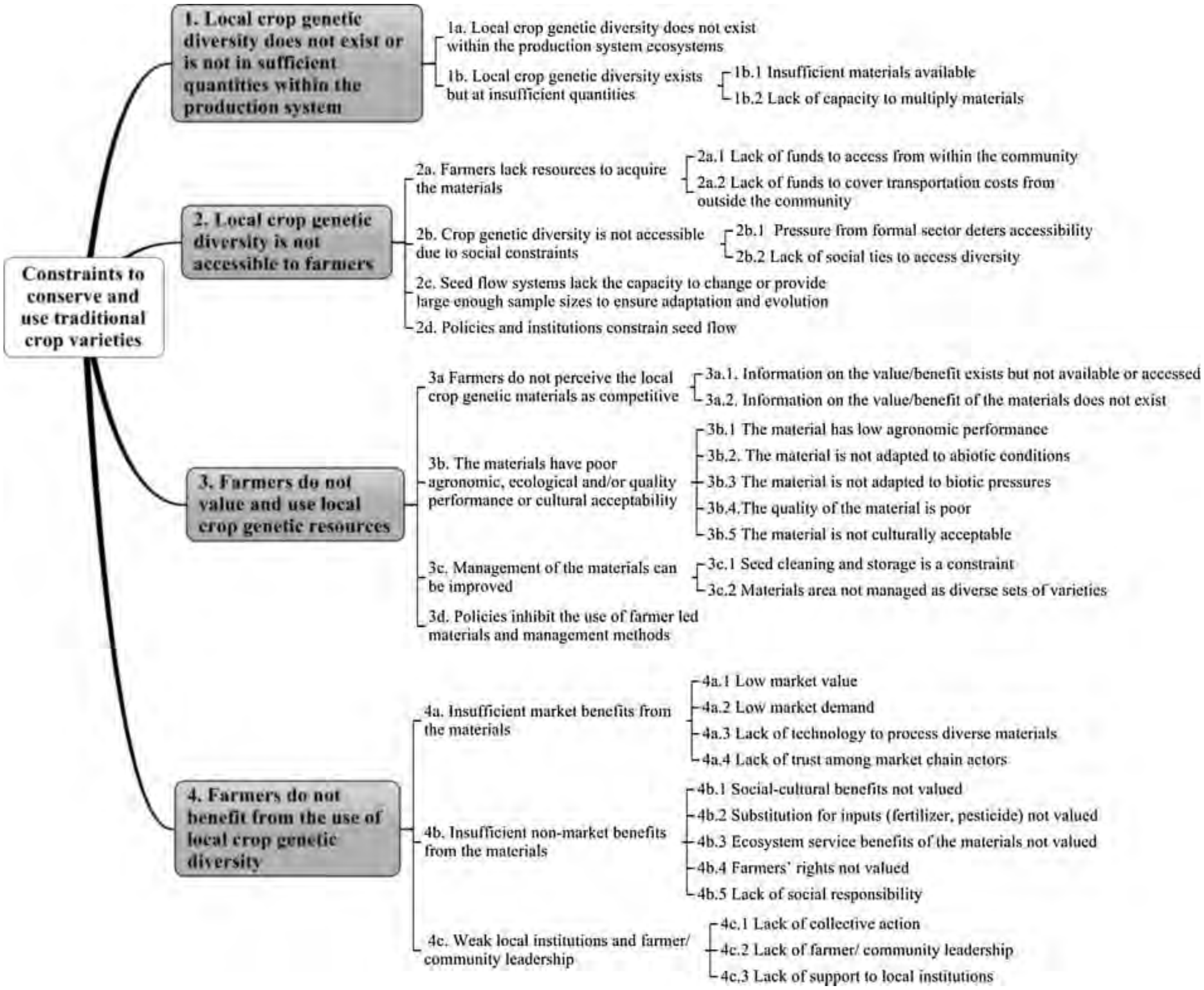

FIG. 1. Heuristic framework for identifying constraints and related actions to support the conservation and use of traditional crop varieties within agricultural production systems.

2003; Tanto *et al*., 2009), apricot (Baymetov *et al*., 2009), walnut (Butkov and Turdieva, 2009; Djumabaeva, 2009), apple and pear (Djavakyants, 2010), and grape (Djavakyants, 2009; Turgunbaev, 2009). While the numbers of varieties provides a useful first approximation of the extent and distribution of diversity, there has been discussion both of the extent to which variety names adequately reflect agro-morphological, biochemical or molecular diversity, and of whether variety names are used consistently by farmers at different geographic scales.

Sadiki *et al*. (2007) reviewed studies which correlated names of varieties to the agromorphological descriptors used by farmers. He and his colleagues compiled information globally for different communities, which suggested that variety names, when complemented by farmer descriptions, could be used as a basis for arriving at estimates of traditional variety numbers, and provide a useful estimate of the amount of genetic diversity within the farmers' production systems. As shown by Jarvis *et al*. (2008), variety names can also be used to provide a valuable global estimate of diversity, focusing attention on the role of farmers themselves in the maintenance of crop diversity in production systems.

Variety names also provide information on the nature, status and management of varieties. Nuijten *et al*. (2008) found that three types of names could be distinguished for rice in the Gambia; those referring to common old varieties, common new varieties, and uncommon varieties, thus showing that variety names supply information on the period of time the variety was used in a village and on the flow of varieties between and within villages. The farmers' or community beliefs that a named recognizable population has particular properties and identity is likely to lead to management practices that tend to reinforce separate identities. This creates a powerful selection practice able to maintain the preferred traits in specific populations (Brown and Brubaker, 2002).

Methods to analyze diversity information when farmers use the same name for different varieties or different names for the same varieties, have been discussed by Chavez-Servia *et al*. (2000), Arias *et al*. (2000), and Tuxill *et al*. (2009) for maize and beans in Mexico, by Sawadogo *et al*. (2005) for sorghum in Burkina Faso, by Karamura and Mgnezi (2004) and Gold (2002) for banana, and by Bajracharya *et al*. (2006) and Bisht *et al*. (2007) for rice. Gender has been shown to play a role in the number of descriptors used (Rijal, 2007), and the type of characteristics described (Karamura *et al*., 2004). The work has also shown the importance of using information from farmers on the traits they use for distinguishing their traditional varieties, to define consistent units of farmer managed diversity (Sadiki and Jarvis, 2005).

A range of studies is now available which have tried to quantify the amount of diversity within farmers' fields by comparing the descriptions given by farmers to distinuguish their varieties according to agromorphological field data: in faba bean (Sadiki *et al*., 2001; 2002), barley (Tsehaye *et al*., 2006; Tanto *et al*., 2009), maize (Mar and Holly, 2000; Arias, 2004; Burgos-May *et al*., 2004; Latournerie-Moreno *et al*., 2006) and taro (Rijal, 2007; Canh *et al*., 2003; Hue *et al*., 2003). Other studies have examined the diversity of adaptive and ecophysiological traits within the production system (Teshome *et al*., 2001; Weltzien *et al*., 2006; Thinlay *et al*., 2000; Hue *et al*., 2006). The diversity of quality and nutritional traits (Duch-Gary, 2004; Cazarez-Sanchez, 2004) has also been described, as has the relationship of levels of crop genetic diversity to geographical regions (Taghouti and Saidi, 2002; Bouzeggaren *et al*., 2002; Teshome *et al*., 2001).

Brown and Hodgkin (2007) reviewed some of the molecular methods available to assess the extent and distribution of diversity, including single nucleotide polymorphisms (SNPs), phylogentic analysis (Clegg, 1997; Brown and Brubaker, 2000) and functional genomics (Aharoni and Vorst, 2001; Peacock and Chaudhar, 2002). Kumar and colleagues (2009) reviewed the potential advantages and disadvantages of different molecular markers in assessing genetic diversity, while Witcombe *et al*. (2008) reviewed the use of traditional and new genomic technologies for breeding for tolerance to abiotic stress of low nitrogen, drought, salinity and aluminum toxicity. Laurentin (2009) recently synthesized data analysis methods for molecular characterization of plant genetic resources.

Various studies have tried to compare the descriptions supplied by farmers to distinguish their crop varieties by means of agromorphological, biochemical and molecular descriptors, so as to provide an overall diversity assessment in traditional varieties. In some cases, genetic data have substantially confirmed information that the number of traditional varieties distinguished by their names is a good representation of diversity within a production system. In other cases, names were not correlated with diversity patterns of either agromorphological or molecular descriptors, but with the sets of traits farmers used to describe different units (Sadiki *et al*., 2007; Baymetov *et al*., 2009).

Sagnard *et al*. (2008) showed a low correlation between the diversity of farmer names and the genetic diversity assessed by microsatellites for sorghum in West Africa. The relationship between molecular markers, variety names and agromorphological traits, has also been reported to be poor or complex in sorghum traditional varieties from Mali (Chakauya *et al*., 2006), cassava in Uganda (Kizito *et al*., 2007), and sorghum in Zimbabwe (Mujaju *et al*., 2003; Mujaju and Chakauya, 2008). Busson *et al*. (2000) found that farmer management of the outcrosser–pearl millet–resulted in more differences with respect to microsatellite marker variation among farmers, than among same named varieties grown by different farmers; thus, the traits used by farmers to distinguish the different named varieties did not give genetic identity at the molecular level. Pressoir and Berthaud (2004) found that high variation in flowering time among populations of maize in Mexico suggested that these agromorphological traits would be different from those described with molecular markers. In Jumla, Nepal (a high altitude site), over 20 traditional rice varieties were identified by farmers using grain color. These 20 varieties were found to differ with respect to a small number of key morphological traits, and by using SSR analysis had only limited molecular genetic diversity (Bajracharya *et al*., 2001; 2006). In contrast, in the low lands and middle hill sites of Nepal, the richness of farmer named rice diversity agreed with the diversity measured by SSR markers (Bajracharaya *et al*., 2010).

Most of the molecular studies were undertaken using what are believed to be neutral markers on a rather small scale and, particularly for cross-pollinated crops, it is perhaps not surprising that it is difficult to find a good correlation between variety names, or agromorphological traits, and molecular markers. There is a need to collect much more complete data sets using a much wider range of markers.

An understanding of the extent and distribution of diversity using both farmer-determined categories and a range of genetic markers, underpins the identification of ways of supporting the maintenance of traditional varieties. Community biodiversity registers (Subedi *et al*., 2005) (Table 1) enable farmers to maintain information on diversity within their community and to provide the information needed to address bio-piracy concerns. Information on the extent and distribution of diversity also provides the information needed to assess whether there is enough diversity within the system for selection, or whether the system will be able to adapt to environmental and economic change (Figure 1: $1a$, $1b$).

Information on consistency with respect to names is also essential when reintroduction of materials is envisaged and various approaches have been tested to support this process, in Ethiopia and elsewhere (Worede, 1997; Worede *et al*., 2000; Feyissa, 2000; 2006; De, 2000) (Table 1). Ecuador won the 2008 Ecuador Initiative award for the return of 10,000 plants of 15 traditional crop varieties (roots, tubers, grains, and fruit) to local communities (UNORCAC, 2008). In Burkina Faso, a series of local genebanks are being established in high-priority conservation areas. These gene banks are part of the National Plant Genetic resources system and will both emphasize conservation of local varieties and be a source of local seeds that can be deployed in the event of natural disasters such as extreme drought (Balma, *et al*., 2004; Bragdon *et al*., 2009).

B. Patterns of Diversity Within and Among Households, Communities and Landscapes

The analysis of patterns of diversity and the distribution of diversity over greater or lesser areas has provided information on the importance of biological, ecological, environmental, and social characteristics, which can usefully guide the development of supporting management practices for traditional varieties (Brown, 2000). Measurements of richness, evenness and divergence, often used in ecological studies, have more recently been applied to the partitioning of traditional varieties within and among communities on-farm (Jarvis *et al*., 2008). Richness is the number of different kinds of individuals regardless of their frequencies; evenness describes how similar the frequencies of the different variants are, with low evenness indicating dominance by one or a few types (Frankel *et al*., 1995; Magurran, 2003). Divergence is a measurement of the proportion of community evenness displayed among farmers. A recent evaluation of Jost (2010) discusses evenness related to the maximum and minimum possible for a given richness, by decomposing richness into independent diversity and evenness components.

Measurements of richness, evenness, and divergence were used to bring together varietal data of 27 crop species over five continents, collected by partners from over 50 government and non-government institutes, to determine overall trends in crop varietal diversity on-farm (Jarvis *et al*., 2008). As well as showing that considerable crop genetic diversity continues to be maintained on-farm, in the form of traditional crop varieties, this synthesis provides a baseline for estimating future genetic erosion on-farm, and information on the relationship between richness and evenness for traditional varieties maintained at farm and community levels. The results showed that as farmers increase the number of traditional varieties they grow, they often plant relatively even areas for each of the different varieties.

The mode of reproduction (whether inbreeding, outbreeding or vegetatively propagated) of a species is an important factor in understanding the patterns of genetic diversity observed in traditional varieties. The breeding and reproductive systems of crop species affect the farmer's perception of diversity and his or her management practice. Clonal and inbred species are more strongly differentiated genetically and can be more easily separated into identified types or varieties. In a number of cases, fields of clonal or inbred crops are planted to a mixture of traditional varieties, which can later be separated at harvest (Brown, 2000; Jarvis *et al*., 2000). In contrast, for outcrossed species such as maize, a traditional variety appears to be a more polymorphic entity in which any particular genotype is ephemeral (Louette *et al*., 1997; Teshome *et al*., 2001). Hamrick and Godt (1997) summarized the effect of breeding systems on partitioning variation within and among crop populations, with self-pollinating crops showing twice as much population differentiation as outcrossers. Clearly, breeding systems and crop biology are important in identifying supportive management options. Communities and farmers are usually both aware of this and have embedded a variety of procedures for crops with different characteristics (Jarvis *et al*., 2004).

It is widely expected that patterns of diversity will reflect differences in climate, altitude and other agro-ecological factors. In fact, the amount of variation that can be attributed to agro-ecological factors has often been found to be relatively small by comparison with that found within populations, although clustering of varieties with similar agromorphological characteristics has been described (e.g., sorghum in Zimbabwe, Mujaju and Chakauya, 2008). Thus, in rice in Nepal, genetic variation was mostly due to intra-population diversity (within a farmer-named variety) and was independent of agroclimatic zones, variety names, and altitude (Bajracharya *et al*., 2006). In contrast, phenotypic traits in Ethiopian barley arid sorghum were strongly related to altitudinal range (Demissie and Bjørnstad, 2004; Teshome *et al*., 2001). Microsatellite diversity of traditional sorghum varieties across Mali, Burkina Faso and Niger, has shown that sorghum exhibited more genetic diversity in terms of allelic richness in Niger than in Mali, despite a lower agroclimatic range in Niger, suggesting that anthropogenic management practices, together with agro-ecological factors, form the structure of sorghum genetic diversity in this region (Sagnard *et al*., 2008). On balance, the evidence suggests that when introduction of new diversity is planned, it is better to use materials that come from similar agro-ecological zones.

The area in which individual varieties occur varies substantially and while some are maintained very locally, others may be part of extremely extensive seed systems extending over more than one region or country (Louette *et al*., 1997; Zimmerer, 2003; Valdivia, 2005). The agromorphological diversity of 15 traditional maize varieties from a single site, Yaxcaba in the Yucatan State, was comparable with that of 314 maize varieties from all three States of the Yucatan Peninsula (Chavez-Servia *et al*., 2000; Camacho-Villa and Chavez-Servia). Similary, in Morocco, Belqadi (2003) showed that a major portion of agromorphological variation diversity for the Moroccan faba bean was captured in populations from the two northern provinces, and Barry *et al*. (2007) reported that in Guinea each of the villages studied had more than half of the regional allelic diversity of African rice, with genetic differentiation among varieties from the same village accounting for 70% or the regional variation. These studies have helped identify areas where local diversity is representative of a much wider area for a given crop and could be used to reintroduce diversity into a larger area.

At a more local level, the "four cell" analysis has proved to be a useful method of exploring the distribution of varieties in Nepal, Vietnam, Brazil, Ethiopia, Mali, India, Indonesia and Malaysia (Sthapit *et al*., 2006b; reviewed in Sadiki *et al*.,

2007) (Table 1). This approach brings together farmers and researchers to categorize varieties according to whether they are grown by many or few households, and whether they cover small or large areas of the community (Rana *et al*., 2007; Hue *et al*., 2003). Grum *et al*. (2003) used this method to give opportunities to farmers in Sub-Saharan Africa to discuss their perceptions on whether they considered varieties rare or common, or widespread or local for rice, yam, sorghum, millet, and cowpea. The tool can be used too for farmers to collect information for self-directed action at community level (Sthapit *et al*., 2008b).

C. Ensuring the Existence of Sufficient Quantities of Materials

Estimating the extent and distribution of diversity provides the information needed to determine whether there is sufficient diversity of a crop within a production system to meet the various needs of farming communities (Figure 1: 1*b*). This is not always the case, as illustrated by Smale *et al*. (2009) who describe the shortage of well-adapted millet and sorghum seed in the Sahel. They found that local markets were important sources of seed in riskier, more isolated villages, indicating a need to legitimize local seed markets and, perhaps, to separate them from grain markets, through product information including marking with geographic origin. Such studies also provide information that can guide support for local seed systems, the introduction or reintroduction of traditional varieties and conservation actions.

A number of projects and studies have explored the ways in which varieties are best introduced when it is believed that farmers do not have the desired diversity. However, the majority of such programs had the aim of facilitating dissemination of new varieties (Rohrback *et al*., 2002; Tripp *et al*., 2001; Scheidegger *et al*., 2000; Bentlay *et al*., 2001) and took little or no account of existing traditional varieties and traditional seed systems (Tripp, 2006).

While the decision to add new diversity into the farmers' production systems, or to rehabilitate an area with lost diversity, rests ultimately with the farmers, the provision of traditional varieties is associated with a number of difficulties, in addition to those associated with establishing the identity and the range of the desired materials mentioned above. Kouressy *et al*. (2008) have argued that population sizes of varieties should be large enough to allow adaptation. Kouressy *et al*. (2008) have shown that large enough population sizes of traditional sorghum varieties allowed farmers in Mali to shift to short cycle varieties in adaptation to changing environmental conditions. However, few gene banks are equipped to provide sufficient seeds for direct sowing by farmers or to provide population sizes sufficient for adaptation to changing environmental conditions and management practices (Iriarate *et al*., 2000). Further, most genebanks are not easily accessible to farmers and communities. In the absence of a gene-bank, the Western Terai Landscape Project (WTLCP), in Western Terai, Nepal, used a systematic, participatory, seed exchange meeting to exchange seeds of local varieties of traditional crops and vegetables that are neglected by commercial seed retailers and extension system (Shrestha, 2009).

One approach that appears to be successful has involved the development of community seed banks and community gene banks (FAO, 2006a). This has occurred in several countries, including Ethiopia, Nepal, India, Bangladesh and the Philippines (Bertuso *et al*., 2000; Ramprasad, 2007; Poudel and Johnsen, 2009; Swamanathan 2001; De Boef *et al*., 2010) (Table 1). These banks are usually established in collaboration with local organizations and national or regional genebanks, and sometimes universities, to conserve and distribute local varieties through a farmer-led on-farm conservation approach. The selection of the materials to be multiplied relies on an assessment of the local diversity and on ensuring that the diversity of the population of the different traditional varieties is adequately covered. Deciding which varieties to target may be based on whether they are rare versus common, on particular traits for particular soil types or on market opportunities. Empowerment of local communities and their institutions is a precondition to implementing such community-based activities (Cromwell and Almekinders, 2000; Bartlett, 2008). The varieties can be used also to target the niche markets discussed in Section 5 below. The analysis of diversity also provides conservation guidance. Measurements of richness and evenness indicate which varieties are more likely to be lost and how much of the landscape they represent; they guide decisions on the maintenance of representative samples in community seed banks, or in national and international gene banks, or on whether to develop incentive mechanisms to promote endangered varieties.

III. ACCESS TO DIVERSITY

Access to crop seed or planting material diversity requries people having adequate land (natural capital), income (financial capital) or connections (social capital) to purchase or barter for the varieties they need (Sperling *et al*., 2008). Used in this sense, "seed" includes other planting materials such as tubers, cuttings or bulbs. Farmers may not have the desired access they need because they lack the resources necessary to acquire planting materials. They may lack funds to purchase or exchange the preferred planting material from within their communities (Figure 1: 2*a*.1). Appropriate seeds may not be available within the village, and the farmers may lack the resources to go to where seeds are being sold or exchanged (Figure 1: 2*a*.2). Planting materials for traditional varieties may also not be accessible due to social constraints. There may be pressure from both formal extension services and community peers against obtaining and using planting materials of local varieties (Figure 1: 2*b*.1). In addition, a farmer may lack the correct social ties or social status to obtain varieties (Figure 1: 2*b*.2). Seed quality and seed management practices can also be an issue and are discussed in Section 4, as can seed regulations (Figure 1: 1*d*). The availability of materials and the ways in which farmers access and manage seeds are expected to affect genetic diversity both within and among traditional varieties and, over time, may lead to changes in patterns of diversity (Hodgkin *et al*., 2007; Figure 1: 2*c*).

A. Seed Sources, Scale, and Patterns

The seed system is composed of individuals, networks, institutions and organizations involved in the development, multiplication, processing, storage, distribution and marketing of seeds (Maredia and Howard, 1998; Locha and Boyceb, 2003; Dominguez and Jones, 2005). Seed flows influence the pattern and dynamics of material that move in and out of the farmers' systems, and analysis of these flows give an insight into the constraints farmers face in acquiring preferred and quality planting material at the time it is needed for planting (Brocke vom *et al*., 2003).

Although there is no one systematic way in which farmers acquire and manage seeds, many, if not most rural farming communities in developing countries continue to use traditional or informal sources to meet most of their seed needs (Almekinders *et al*., 1994; Gaifani, 1992; Hardon and de Boef, 1993; Tripp, 2001; Cromwell *et al*., 1993; Tahiri, 2005; Muthoni and Nyamongo, 2008; Thijssen *et al*., 2008). The seed a farmer plants may have been selected from his or her own crop in the preceding season, exchanged or purchased from other farmers or institutions, or be a mixture of seeds from a combination of sources (Jarvis *et al*., 2000; Bellon and Risopoulos, 2001; Sperling and Mcguire, 2010; Badstue *et al*., 2002: Asfaw *et al*., 2007). Recent studies have quantified the amounts of farmers' own saved seeds versus seeds obtained from friends, relatives, neighbors, or local markets, and have confirmed that farmers prefer to save their own seeds in most situations (Gildemacher *et al*., 2009; Rana *et al*., 2008; Hodgkin *et al*., 2007; Lipper *et al*., 2010). These studies have described a range of techniques and opportunities that farmers use under different circumstances to access and save seeds (Cromwell and Almekinders, 2000). The different practices used are expected, over a period of years, to produce a dynamics of movement and mixing in which the progenies of individual populations are transferred among farmers, become mixed during exchange or marketing, become sources for new exchanges, or are lost.

Farmers' demands for off-farm seeds often result from an emergency, which may be personal (poor health, individual production failure) or more general (floods, drought, war), and affect the whole community or region. Reasons identified for accessing new seed stocks include low yields, consumption or sale of seed stocks, poor seed quality, the desire to access new varieties, and changes in national policy that affect subsidies and grain imports (Tripp, 2000; Mosely *et al*., 2010). There have been a number of studies on the ability of informal seed systems to meet users' needs during emergencies and disasters, such as floods, drought, or war (Almekinders *et al*., 1994; Richards and Ruivenkamp, 1997; Sperling, 2001; Asfaw *et al*., 2007). In a number of cases, informal markets were found to be critical to restocking traditional variety seed resources, both in normal and stress periods (Sperling and Mcguire, 2010). Diversity fairs, diversity-kits, micro-credit schemes, and community seed banks are also interventions which can increase access (e.g. Mazhar, 2000; Sthapit *et al*., 2006a, c, d; UNORCAC, 2008) (Table 1).

Seeds may be acquired via cash transactions, barter, as gifts, by exchanging one variety of seed for another, as a loan to be repaid upon harvest, or even by surreptitious expropriation from another farmer's field (Badstue *et al*., 2002; Mbabwine *et al*., 2008). Seeds of varieties developed by the formal sector are often maintained and distributed informally (Mellas, 2000; Bellon and Risopoulos, 2001), largely independently of government institutions. In some societies, there is a significant dependence on farmer-to-farmer seed transactions for traditional varieties (Hodgkin *et al*., 2007) as these sources are regarded as more trustworthy than alternatives such as local markets (Latourniere-Moreno *et al*., 2006). In South Asia, community seed banks are becoming an increasingly important intervention which also preserves local varieties and provides a source of local material for seed multiplication (Mazhar, 2000; Satheesh, 2000).

Various approaches are being used by non-government and government research, education and development agencies at local and national levels to support seed acquisition and increased numbers of transactions within and among communities, including community seed banks and seed diversity fairs (Tapia and De la Torre, 1998; Guerette *et al*., 2004; Shrestha *et al*., 2006; UNORCAC, 2008; De Boef *et al*., 2010) (Table 1). During a diversity fair, farmers from different communities are brought together to exhibit a range of landraces: this allows farmers to locate rare and unique diversity and provides an opportunity to exchange seeds and associated knowledge. Participatory seed dissemination (Rios, 2009) integrates seed diversity fairs and farmers' seed experimentation and dissemination. Seeds from diversity fairs are tested in the farmers' production systems to be further multiplied and diffused to other farmers. Identifying whether there are farmers who are known for reliably and regularly producing a good crop which provides seeds of high quality can be important for developing local practices that help maintain traditional varieties.

Analysis of patterns of seed transfer and exchange of traditional varieties provides important information for maintenance of traditional varieties helping to assess, for example, the effective population size, extent of mixing, degree of gene flow, and existence of defined subpopulations (Hodgkin *et al*., 2007). Studies among diverging subpopulations in model systems have shown that an uneven migration rate reduces the effective population size of the system, particularly when the seed of one farm is replaced (Maruyama and Kimura, 1980; Wang and Caballero, 1999; Whitlock, 2003). Heerwaarden and colleagues (2010) have used empirical data from maize in traditional agricultural systems in Mexico to demonstrate that seed dynamics in human-managed environments differ from existing mega-population models of natural ecosystems. In particular, the assumptions of most meta-population models (Kimura and Weiss, 1964; Slatkin, 1991, Wang, 1997) as to the absence of population bottlenecks following extinction and single-source migration, do not apply to systems under farmer management (Louette *et al*., 1997; Dyer and Taylos, 2008; Heerwaarden *et al*., 2010). High levels of pollen migration, such as occur in cross-pollinated crops such as maize and pearl millet may mask the effects of seed management on structure (Heerwarrden *et al*., 2010). In general it seems that farmer selection practices may not be a constraint in terms of having the diversity needed, as long as the effective population sizes are large enough to allow for evolution and adaptation, supported by adequate seed or gene flow.

Seed migration in traditional varieties can be fairly local–within communities or among neighboring communities (Collado-Panduro *et al*., 2005; Mar, 2002; Bela *et al*., 2006; Latourniere-Moreno *et al*., 2006; Banyia *et al*., 2003). Along the central Amazon River in Peru, most seed exchange of maize, cassava, peanut, chili peppers and cotton, occurred within rather than among the 13 communities. This seemed to reflect difficulties of access and communication among communities. Similarly, Tanto *et al*. (2009) found that seed flow for barley does not occur independently across the years within two seasons in areas of Ethiopia where there are two cropping seasons for the crop. Sagnard *et al*. (2008) found no genetic structuring among traditional sorghum varieties in villages in Burkina Faso, Mali and Niger, indicating that traditional seed systems operate at a very local scale in these study sites. However, some seed networks can be extensive covering distances that cross national boundaries and ecosystems (Zimmerer, 1996; Valdivia, 2005; Coomes, 2001).

While farmers may prefer to obtain desired seeds from others immediately after harvest, they may also need to obtain seeds at planting time when germination failed. At this point, farmers often have little choice in the variety obtained although they may try to obtain material from a microenvironment similar to theirs (Rana, 2004). Usually under such situations, farmers rely on social connections for their immediate needs, but community seed banks can be seed sources. Community biodiversity registers can provide information to locate the relevant variety within the community, but this requires very good documentation of local crop diversity in the register (Subedi *et al*., 2005), as well as access by farmers to the information. In cases of difficulty in acquiring seeds, local markets, middlemen, NGOs and experts, or nodal farmers, become increasingly important as sources of seed supply (Table 1).

B. Seed Custodians and Social Networks

Trust has been shown to be an important factor in farmers' choice of which seeds to acquire (Badstue, 2007). Public extension services may not always be seen as a trusted source, because the system is perceived to deliver too narrow a range of varieties which are not suited to the diverse growing conditions that a farmer may be managing (Adato and Meinzen-Dick, 2007). The response to seed needs is usually to look first for a family member or a friend as a reliable source (Almekinders *et al*., 1994; Badstue *et al*., 2007; Barnaud *et al*., 2008), and social relations play an important role in seed acquisition throughout the world (e.g., Ethiopia; McGuirre, 2008). Poudel *et al*. (2005) reported that communities with weak social networks are more vulnerable to accessing locally adapted seeds in adverse conditions, compared to those with strong social networks. Social seed networks can be strengthened by interventions that improve access to existing varieties and new diversity (e.g., seed fairs, diversity kits, community seed banks, participatory variety selection programs; Table 1). With better exposure of farmers to breeding skills and knowledge, participatory plant breeding (PPB) can strengthen farmer seed systems and promote on-farm management and sustainable use of local crop diversity (Sperling *et al*., 2001; Almekinders *et al*., 2006; Halewood *et al*., 2007) (Table 1).

Access to seeds may require appropriate social ties and kin networks (Lopez, 2004). Heritage and cultural identity values can be enhanced when a traditional variety is acquired from someone who is a relative or an elder in the community (Meinzen-Dick and Eyzaguirre, 2009). Analysis of rice seed supply networks in Nepal (Subedi *et al*., 2003) revealed their complexity and dependence on a range of social variables. In many communities, certain individuals may act as nodal farmers, characterized by their involvement in a large number of exchanges (Subedi *et al*., 2003; Subedi and Garforth, 1996). Further investigation has shown that the people who act as"nodal" farmers may change from one year to another (Poudel *et al*., 2008). Social prestige and religious values can be used to enhance the incentives to both maintain and share traditional crop varieties (Meinzen-Dick and Eyzaguirre, 2009).

Seed networks can be dependent on gender, wealth status, and age (Lope, 2004; Rana *et al*., 2008; Howard, 2003; Sillitoe, 2003; Song and Jiggins, 2003; Morales-Valderrama and Quiñones-Vega, 2000), but in some cases, they have been found to be gender-independent (Subedi and Garforth, 1996). Poor women often have less access to finance, markets, technologies, education systems, thus inhibiting ability to diversify (Vernooy and Fajber, 2004). Community seed networks, which were men-men, men-women (men led), women-men (women led), and women-women, have all been found in certain communities (Belem, 2000; Okwu and Umoru, 2009).

Gender, wealth, social status, and market-related variables have different effects on diversity in different parts of the world. In Ethiopia, education positively influenced the amount of diversity on farm for maize, wheat, and teff, but not for barley. Female-headed households grew more evenly distributed wheat varieties. Households with substantial outside sources of income grow a greater range of barley varieties, but this was not the case for maize (Benin *et al*., 2006). Labour policies that affect household labour supply and its composition are likely to have a large impact on traditional crop variety diversity. Loss of adult male labour has been correlated with the reduction of the diversity of crops and varieties grown (Van Dusen, 2006; Gauchan *et al*., 2006). Several studies have found that female-headed households are more likely to grow more traditional varieties (Gauchan *et al*., 2006; Edmondes *et al*., 2006; Benin *et al*., 2006; Dossou, 2004).

A number of ways to support key groups and hence increase the use of traditional varieties have been proposed and tested (Table 1). Most methods include training key seed producers and women in seed cleaning, multiplication and distribution and support for local institutions and social networks. Common approaches involve the development of community seed banks and diversity fairs and the identification of reliable farmers who can underpin farmer-to-farmer exchanges, as in Syria (Aw-Hassan *et al*., 2008). Diversity seed fairs that are organized by public institutions together with communities or non-governmental organizations, can help to increase transparency in seed quality and bridge knowledge across institutions and farmers on variety quality (Meinzen-Dick and Eyzaguirre, 2009; Nathaniels and Mwijage, 2006). Such interventions are likely to work best when the characteristics of the different families, communities and groups (gender, ethnic, religious, and wealth) who are most likely to conserve diversity are known (Smale *et al*., 2004).

C. Adaptability and Change

The characteristics of the seed systems and the ways in which they change over time are likely to have a substantial impact on the genetic diversity present in individual crops and varieties. The seed systems of specific crops are subject to substantial variation in the availability of different materials as a result of variation in production, market fluctuations, government policies, climate variability, and in the framework of catastrophes such as droughts and hurricanes (Latourniere-Moreno *et al*., 2006). The ability to access seeds promotes resilience in the farmers' production systems. Access to seeds can buffer against uncertainty and periods of rapid change across temporal and spatial scales. Lack of funds to purchase seeds, particularly during times of environmental uncertainty, reduces where coping strategies are needed, such as high seeding rates to counter uncertainty (Mcguire, 2007; Tuxil *et al*., 2009; Latourniere-Moreno *et al*., 2006; Bisht *et al*., 2007). Analysis is needed to ensure that the planting materials have enough diversity to adapt to farmer selection and management. Modeling social-ecological systems are needed to explore attributes that affect resilience, particularly in systems with high predictability (Walker *et al*., 2010).

The extent of migration can change substantially from year to year with significant migration occurring in years where production is poor, or as a result of major seed losses through disasters such as floods and hurricanes (Hodgkin *et al*., 2007). In the Western Terai of Nepal, farmers maintain a portfolio of local rice varieties (usually of short duration such as Sauthariya) to replant the crop when total crop failed because of stochastic events or poor rain after planting (Bhandari, 2009). Every year small nurseries are maintained for such cultivars in case the crop fails by community seed banks where farmers "borrow" seeds at planting time and return them after harvest (Table 1).

D. Seed Regulations and Access to Diversity

Farmers' ability to maintain and acquire seed from the informal sources described above may be affected by the establishment of formal seed systems, e.g., seed distribution and release systems are regulated and monitored by the state (Figure 1; 3*d*). The original elements that defined the formal seed systems were put in place as a result of the development of specialized plant breeding products in Europe in the mid-nineteenth century, in order to create transparency in a seed market where variety names were rapidly proliferating. (Bishaw and Van Gastel, 2009; Louwaars and Burgoud, *in press*). Current variety registration for commercial purposes requires that the new variety be distinct from all varieties of common knowledge, uniform in its essential characteristics and highly stable after repeated multiplication (DUS = Distinctness, Uniformity and Stability, Bishaw and Van Gastel, 2009). These criteria guarantee that when a farmer buys seeds of a registered variety, these will be indeed of that variety and it will perform as such over time. In addition, testing for cultivation and use values (VCU) was introduced as a requirement for commercial release, in order for farmers to have an independent assessment of the yield, quality and value of the grain. As developing countries have established seed production systems greatly inspired by the ones in Europe, they have adopted seed certification and variety registration schemes that are similar to the European model (Louwaars and Burgoud, *in press*; Grain, 2005).

Some civil society organizations, organic food producers and environmentalists have denounced the rigidity of the uniformity criteria, and the costs involved in variety registration and seed certification, which make the formal system unfriendly for farmers' varieties such as landraces and new varieties developed through participatory plant breeding, leaving these varieties outside the legal market of seeds (Farm Seed Opportunities, 2009). In addition to limiting the opportunities for farmers to obtain revenues from the varieties they produce, this situation results in less genetic diversity available in the market and may ultimately threaten diversity on farm (Leskien and Flitner, 1997; Louwaars, 2000; Kastler, 2005; Farm Seed Opportunities, 2009).

A number of studies have shown that the formal seed sector does not have the capacity to supply the variability needed in low input farming systems, nor to meet the need for locally adapted varieties (De Boef *et al*., 2010; Kesavan and Swaminathan, 2008; Lipper, 2010). Common figures suggest that the formal system provides for around 15% of the total seeds used by farmers in developing countries (Cooper, 1993; FAO, 1998; 2010; Hodgkin *et al*., 2007), although the situation varies by crop and region. In Europe, there is still an important demand for traditional varieties among small farmers and amateurs for direct cultivation and for participatory breeding programs sponsored by organic agriculture associations (Toledo, 2002; Negri, 2003; Chable, 2005; Negri *et al.*, 2009). According to European Union regulations, farmers are allowed to reproduce non-certified seeds for themselves, but they are not able to sell it. Depending on how strict governments are, exchange of non-registered seeds may be considered illegal as well (Louwaars and Burgaud, in press). The situation in developing countries is quite different: Seed regulations are rarely enforced at the local level, and both traditional and modern varieties are exchanged freely among farmers and sold in local markets (Louwaars, 2002). However, the existence of a formal seed system can affect the dynamics of the informal systems and have an impact on the diversity available to farmers. Firstly, the use of certified seeds of modern varieties is either recommended by extension services, linked to credit facilities and subsidies, or is obliged by the processing industry (Jaffe and Van Wijk, 1995; Tripp, 1998, Pascual and Perrings, 2007; Mosely, 2010). Subsidies can lock farmers into a pest-control technology linked to the distribution of modern crop varieties (Wilson and Disdell, 2001). Secondly, the illegality of selling noncertified seeds discourages the development of alternative models of seed supply (Birol, 2007; Lipper, 2010).

Different models have been proposed and tested to create a space for different ways of seed production and supply, within the formal seed system. Keeping the formal system's original objectives of providing transparency and ensuring seed quality, these models try to address the information gaps commonly found in informal seed systems by regulating the commercialization of traditional and modern varieties in a way that better adapts to farmer and small breeder needs. The European Union has recently approved a special treatment for the so called conservation varieties by which landraces adapted to local and regional conditions and threatened by genetic erosion can be registered for commercialization under certain conditions.[1] The special treatment consists, of 1) a certain degree of flexibility in the level of uniformity that is required, and 2) an exemption from official examination if the applicant can provide sufficient information about the variety through other means such us unofficial tests and knowledge gained from practical experiences. In Nepal, the uniformity requirements of the Nepalese Seed Act were applied in a relaxed manner in order to accommodate farmers' application for the registration of certain varieties developed by participatory plant breeding together with traders and hoteliers in 2006 (Gyawali *et al.*, 2009; Halewood *et al.*, 2007). In Argentina, seeds of ancient varieties of forages can be commercialized as "Clase Identificada Común" (Common Identified Variety), without indicating the name of the variety on the seed package. An alfalfa landrace known as alfalfa pampeano can therefore be sold under the general name of alfalfa seed. Since the name of the variety is not required in this case, the landraces can be legally sold without having to meet the DUS criteria required for variety registration (Gutierrez and Penna, 2004). This alternative, however, may lead to information gaps once the landraces' seeds are commercialized beyond a limited and reliable circuit.

Some countries recognize partial or full auto-certification systems for traditional varieties (Table 1). The Quality Declared Seed System proposed by the Food and Agriculture Organization of the United Nations (FAO, 1993) has been widely used in areas where seed markets are not functional and government resources are too limited to effectively manage comprehensive certification systems. Under this system, seed producers are responsible for quality control, while government agents check only a very limited portion of seed lots and seed multiplication fields. The system has been recently revised with the aim of recognizing the role of national policies and providing a clearer explanation on how quality declared seeds can accommodate local varieties (FAO, 2006b).

IV. IMPROVING USE THROUGH BETTER INFORMATION, MATERIALS AND MANAGEMENT

The use of the traditional crop diversity by farmers or communities might often be increased (i) if there were more information on the characteristics (eco-physiological, adaptive, quality traits) or uses of these materials, (ii) if the materials themselves were enhanced, or (iii) if the agronomic management of the materials were improved. Farmers may perceive that traditional varieties are not competitive with other options because of a lack of characterization and evaluation information on the varieties, or because of a lack of information on appropriate management methods (Figure 1: 3*a*). This lack of information may occur either because the information does not exist, e.g., the varieties have never been characterized or evaluated on farm (Figure 1: 3*a*.2) or because the information is not available to the user community (Figure 1: 3*a*.1).

Even when traditional varieties meet some of the farmers' needs, there may be a number of constraints which limit their use and prevent them reaching their full potential. Thus, environmental or market conditions may have changed, or varieties may have become susceptible to new pests and diseases (Figure 1: 3*b*). If the varieties available to the community lack the diversity needed to adapt to these changes, new materials may be needed with the required traits, or different management methods that improve the performance of the varieties may be required (Figure 1: 3*c*).

A. Producing and Providing Characterization and Evaluation Information for Traditional Varieties

Farmers who have to access seed from other sources have to depend on information offered by the seed provider or on common shared knowledge on traits, consumption characteristics, environmental adaptation and seed quality etc. to manage their crops. Often their information about crop varieties

---

[1] Directive 2008/62/EC of 20 June 2008 provides for certain derogations for the acceptance of agricultural landraces and varieties which are naturally adapted to the local and regional conditions and threatened by genetic erosion and for marketing of seed and seed potatoes of those landraces and varieties.

is extremely limited (Tripp, 2001) and seeds obtained from farmers, market vendors, or seed companies are frequently reported to be accompanied by a lack of adequate information (Badstue, 2007). Farmers may also lack access to information on management methods, particularly, for example, for nursery practices for fruit trees (Oyedele *et al*., 2009; Shalpykov, 2008).

There is a widening recognition by the agricultural research and development community of the value of farmer knowledge, and an increasing use of new information and communication technologies to disseminate this information (Ballantyne, 2009; Kesavan and Swaminathan, 2008; Liang and Brookfield, 2009). Despite the reports that farmers often lack information (as noted above), there are also reports that farmers exchange information on individual varieties, local uses of plant parts, cropping systems, and eating qualities, along with seeds (Rijal, 2007). Farmers also share ecological information together with seeds through local networks. The technical messages derived from failures are shared among local farmers faster than those associated with success (Rijal, 2007; Rana, 2004; Shah *et al*., 2009). In some cases, information may be shared through cultural media, such as folksongs that characterize different traditional varieties and promote genetic enhancement in Ethiopia (Mekbib, 2009) (Table 1).

Lack of both formal and informal inter-agency and inter-ministerial (e.g., ministries and departments of the environment and of agricultural) information sharing is a barrier to successful policy formulation to support innovative land management technologies and strategies that support local crop genetic diversity in the production system (Grarforth *et al*., 2005). Robertson and Swinton (2005) and Pretty and Smith (2004) discuss the increasing importance of new communication methods among agricultural professionals and farmers. Modern information and communication technologies in village-based knowledge centers have been used to provide timely and local-specific information that meets farmers' demands (Kesavan and Swaminathan, 2008). Nursery growers in Central Asia and India can now access information related to scion and rootstock compatibility, and contact custodians of diversity of both mother plants (scion block) and rootstocks (Kerimova, 2008; Djavakyants, 2010; Singh, *pers. Comm*., 2010) (Table 1). Radio and television are also effective and easily accessible sources of agricultural information (Shah *et al*., 2009; Baral *et al*., 2006; Ballantyne, 2009; Balma *et al*., 2005) (Table 1). In the developed world, networks of weather stations in farming regions are becoming the norm. Farmers tap into these for real-time weather data. A relatively inexpensive weather station can be purchased for a farmer community and added to a free weather network such as Wunderground Weather (http://www.wunderground.com/weatherstation/index.asp#hardware) (Table 1).

In addition to information, access to traditional varieties may often be limited within the community, even when a sufficient quantity of seed is available (Badstue, 2006), simply because of poor access to information, weak social networks, social exclusion, and weak institutional mechanisms for collective actions (Sthapit and Joshi, 1996; Shrestha *et al*., 2006) (Figure 1: $3a.1$). In some instances, many farmers may not be aware that useful resources are available, particularly when a variety is only grown by a few farmers within a community (Sthapit and Rao, 2009). For example, Sthapit *et al*. (2006d) reported that while aromatic sponge gourd was grown by only a few farmers in a mid-hills community in Nepal, the number increased significantly after a diversity fair was organized and locally multiplied seeds were distributed.

Most of the work on the evaluation and characterization of traditional varieties is undertaken in the context of the description of materials from genebank collections (Dudnik, *et al*., 2001; Fowler and Hodgkin, 2004). It has been suggested that this may have limited value with respect to evaluation data, as many traditional varieties are specifically adapted to their abiotic and biotic environment (Budenhagen, 1983; Harlan, 1977; Teshome *et al*., 2001). Recently, there has been an increased interest in testing varieties collected directly from farmers and in comparing their performance with modern varieties (as checks or controls) under low input conditions, in order to have data that compares traditional varieties with other options available to farmers (Bouhassan *et al*., 2003; Tushmereirwe, 1996; FAO, 2010). These studies have included multi-locational trials on farm and on research stations for adaptive traits such as drought tolerance (Sadiki, 2006; Jackson *et al*., 2008); Magorokosho *et al*., 2006; Weltzien *et al*., 2006), salt stress (Rhouma *et al*., 2006; Hue *et al*., 2006), nitrogen fixation (Sadiki, 2006), cold tolerance (Thinlay, 1998; Thinlay *et al*., 2000) and disease resistance (Trutmann et. al., 1997; Gauti *et al*., 2005; Finckh and Wolf, 2007). In one study, the relative performance of rice varieties was tested by reciprocal planting in different moisture regimes using upland, rain-fed and irrigated rice ecosystems. Interestingly, the results showed that some rice varieties had higher yields outside their home environments (Rijal, 2007).

While traditional knowledge (and variety names) may provide some information about the nutritional value of different varieties, specific macro- or micro-nutrient data is often not available (Worede, 1997). Laboratory evaluations comparing nutritional levels among traditional and modern varieties for Bangladesh rice showed that some of the traditional varieties had higher iron and zinc contents than modern ones (Kennedy and Burlingame, 2003). Similar work has been done to compare protein levels across traditional and modern bean varieties (Cazarez-Sanchez, 2004; Cazarez- Sanchez and Duch, 2004) and levels of hotness in chili varieties in the Yucatan, Mexico, (Cazarez-Sanchez *et al*., 2005). Hotness was related also to the different dishes prepared with chili. Surprising little characterization of traditional varieties for systems that adopt certified organic agricultural practices has been done until very recently in Europe (Dawson *et al*., 2008; Bengtsson, 2005).

It is important that characterization and evaluation studies are done under farm conditions, in sites that are accessible to farmers and include appropriate modern varieties as controls or checks. Farmers often do not have sufficient capital or time to experiment with allocating their varieties to different production spaces in replicated trials. Growing varieties from different areas together in replicates on farmers' fields offers farmers the chance to observe comparative reactions of traditional and modern varieties. Interventions, such as the establishment of diversity blocks by community seed banks, and the organization of farm walks, cross-site visits for farmers, or other community events, can act as platforms for social learning. An important aspect is to provide the platform at the community level that allows farmers and researchers to interact and learn.

B. Improving Traditional Varieties

Improving the performance of traditional varieties in participatory crop improvement programs has been undertaken in many programs over the last decade, particularly in low input systems (Table 1). Some of these programs have involved the identification of agronomic traits with molecular characterization so as to exploit the local diversity and produce varieties that are superior in marginal environments, but have a broad genetic base (Chiffoleau and. Desclaux, 2006; Ceccarelli and Gando, 2007; Dawson *et al*., 2008; Gyawali, *et al*., 2007; Joshi *et al*, 2001; Sthapit *et al*., 1996; Witcombe *et al*., 2005; Ceccarelli *et al*., 2009; Danial *et al*., 2007; Almekinders *et al*., 2006; Ortiz *et al*., 2009; Valdivia Bernal *et al*., 2007; Marquez *et al*., 2009). Participatory or decentralized crop improvement begins with an understanding of the farmers' preferred criteria, and often includes describing the management methods that farmers use for selecting the next generation (Smith *et al*, 2001, Mekbib, 2008; Nkongolo *et al*., 2008; Jarvis and Campilan, 2007) (Table 1). Traditional varieties may be improved both by preserving traits which are preferred by farmers and by adding additional traits (e.g., pest resistance) to a preferred traditional variety; the process can be implemented at a large number of locations (Lacy *et al*., 2006). The process helps to link farmer and breeder choices, and analyze tradeoffs that might differ among farmers' and breeders' choices (Gauchan *et al*., 2006). Setting collaborative breeding goals with farmers in Nepal for improving the traditional rice variety *mansara,* adapted to poor soils, resulted in the development of the improved variety, *mansara-4.* This variety is now spreading to areas where no other rice variety could be grown (Sthapit *et al*., 2006a; Gyawali *et al*., 2007).

In several countries resistance breeding procedures are integrating farmer selection and using local material and participatory breeding to improve other production and quality traits of locally-resistant varieties, as well as improving the resistance of locally adapted non-resistant varieties (Mgonja *et al*., 2005; FAO, 2010). Varieties that are made available from participatory programs are most likely to spread through existing seed systems. It is therefore important that methods used to improve crop material and seed quality take account of and are linked to seed supply systems (Bishaw and Turner, 2008; Gyawali *et al*., 2007).

A major concern for farmers is seed quality including purity, high germination rates, and reduced disease problems (Weltzien and vom Brocke, 2000; vom Brocke *et al*., 2003; Asfaw *et al*., 2007). Studies on traditional variety seed germination rates (Celis-Velazquez *et al*., 2008) and resistant to post-harvest pests (Teshome *et al*., 1999) have compared relative levels for traditional and modern varieties and found traditional varieties to perform well in many cases. Village seed systems certainly maintain the identity of varieties and, in central Mozambique, have been shown to maintain the purity of varieties and supply quality seed (Rohrback and Kiala, 2007). On-farm seed quality for traditional sorghum varieties was found to be comparatively good by comparison to modern varieties and met national and regional West Asian and North African standards (Mekbib, 2009). Truthful labeling and declaring the source of seed is being used to ensure quality at the community level (Devkota *et al*., 2008). Actions such as seed sorting machines, training in seed quality improvement, seed health, and processing can improve seed quality. Seed cleaning technology for seed-borne diseases, normally recommended for certified varieties, has been used on traditional varieties to increase faba bean yield for traditional varieties by almost 50% (Sadiki *et al*., 2002). Recommendations have been made to expand agricultural extension packages to include traditional varieties with improved management methods (Jarvis and Hodgkin, 2008).

C. Improving the Management of Traditional Varieties

Management practices may also serve to improve the productivity and stability of traditional varieties within the farmers' production system (Figure 1: 3*c*). Planting mixtures of traditional varieties, or of crop populations with high genetic variability, has the potential to reduce pests and diseases on farm (Li *et al*., 2009). Managing sets of varieties or crop populations with different levels of avoidance or tolerance to abiotic stress can decrease the probability of yield loss due to unpredictable rainfall and temperature regimes (Figure 1: 3*c*.2).

The potential negative consequences of planting large areas to single, uniform crop cultivars were recognized as early as the 1930s by agricultural scientists (Marshall, 1977). The Irish potato famine has been cited as one of the most dramatic examples of genetic uniformity leading to devastating loss of crop (Schumann, 1991). Breeding programs continue to develop new varieties and to replace varieties that have lost their resistance to diseases, but the maintenance cost, particularly in developing countries, is high (Strange and Scott, 2005). Resistant varieties may only remain so for a few cropping seasons as new pathotypes emerge (de Vallavieille-Pope, 2004). When resistance in a monoculture breaks down, the whole area of the crop sown to susceptible varieties may succumb while, in a genetically diverse field or variety, it is much less likely that all the different types of resistance present will break down (Mundt, 1991).

Farmers often have local preferences for growing mixtures of cultivars that provide resistance to local pest and diseases and enhance yield stability (Trutmann *et al*., 1993; Karamura and Karamura, 1995; Trutmann *et al*., 1993; Jarvis *et al*., 2007). High levels of diversity of traditional rice varieties in Bhutan has been shown to have high functional diversity against rice blast (Thinlay *et al*., 2000; Finckh, 2003) while high wheat diversity in Italy has been shown to provide yield stability in conditions of low pesticide application (Di Falco and Chavas, 2007). The development of varietal mixtures, or sets of varieties with non-uniform resistance and with lower new pathogens migration or mutation probability of existing pathogens, is in progress in many parts of the world (Finckh *et al*., 2000; Finckh and Wolfe, 2007; Jarvis *et al*., 2007). Such mixtures are based on the analysis of the resistance background, agronomic character, economic value, local cultivation conditions, and farmer preferences.

There is substantial genetic variation for response to water deficit within and among traditional varieties, and a growing literature on the use of a diversity of traditional varieties to minimize risks dues to climatic variability (Sawadogo *et al*., 2006; Sadiki, 2006; Weltzien *et al*., 2006). Drought is a complex stress, influenced by both heat and drought, and plant response also varies according to timing in relation to the plant growth stage and stress intensity (Witcombe *et al*., 2008). Drought tolerance and drought avoidance seem to involve different mechanisms (Yue *et al*., 2006). While no unified abiotic stress resistance mechanism exists (Blum, 2004), there are certainly genes which are involved in responding to a number of different stresses. Planting a range of varieties or multilines with different drought avoidance and resistance properties could be an attractive option for low input systems. Sorghum growers in West Africa use a diversity of traditional varieties with different flowering dates to minimize risks due to climatic variability (Weltzien *et al*., 2006). Lipper *et al*. (2009), have shown that for sorghum farmers in Ethiopia the adoption of a sorghum improved variety, developed to allow drought evasion, was not an effective means of coping with drought and that landraces were more likely to provide the desired drought tolerance characteristics desired by farmers. They also noted that improving education levels among farmers might allow them access to more varieties adapted to low production conditions.

Brown and Rieseberg (2006) compared methods for managing diversity for abiotic and biotic stress that would enable farmers to cope with the stress factors in their production systems. They noted that the scale of variation of abiotic stress both in time and space was greater for abiotic than for biotic stress, that the degree of abiotic stress is less affected by the plant condition than biotic stress, and that divergence is more important that local polymorphism for abiotic versus biotic stress (Brown and Rieseberg, 2006).

Both farmer selection and natural selection can have substantial effects on the seed produced for future crops. Different farmers may have diverging perspectives and management practices in managing their seed stocks and introducing new material. This can result in differences in the time when seed can be provided and in the population structure of the next generation of seeds (Louette *et al*., 1997). Different farmer selection practices (or different participatory selection procedures will affect the genetic make-up and evolutionary dynamics of crop populations (Ceccarelli *et al*., 2009; Scarcelli *et al*., 2007; Barnaud *et al*., 2008; Sagnard *et al*., 2008; Gautam *et al*., 2009). In the case of vegetatively propagated crops, this reflects farmers' variety-specific handling of seed tubers (Zannou, 2009; Scarcelli *et al*., 2006) and genetic effects are likely to result from mutation, epigenetic influences or mixing by farmers.

Marketing at a desirable price can be a problem when farmers do not have storage facilities but must sell their crop to avoid seed or tuber rot (Figure 1: 3*c*.1). Improved storage allows farmers to sell their seeds or grain at periods when the market price is higher (Agbaje *et al*., 2005). Seed storage devices and methods determine the vulnerability of seeds to pests, diseases and physiological deterioration (Gepts, 1990; Latourniere-Moreno *et al*., 2006; Table 1). Post-harvest losses are a serious cause of production losses in developing countries (Grum *et al*., 2003). Improving the air-tightness of storage containers (Wambugu *et al*., 2009; Thamaga-Chitja *et al*., 2004), heat treatment (Beckett *et al*., 2007), manual seed cleaning, and application of non-toxic materials, are some easily applicable methods that combine traditional and modern seed storage technology to reduce the post-harvest vulnerability of seeds (Table 1). Complementary technical solutions will be necessary to integrate the future use of agricultural strategies that include the use of diverse traditional varieties. These may also include adjustments of planting and harvesting to facilitate separation of the harvest products where the handling of mixtures is not possible or not desirable (Finckh, 2008).

D. Improving Policies to Support Farmers Using Traditional Varieties

In general, there are few incentive structures that promote: the conservation and sustainable use of agricultural biodiversity and farmers' customary practices–the heart of Farmers' Rights (2010); Figure 1: 3*d*). Current legal systems make it difficult to adequately recognize the contributions of farmers and farming communities in conserving, developing and using agricultural biodiversity. National and local governments have not yet adequately given a real content to the overused, but so far rather diffuse concept of Farmers' Rights by translating it into practical measures that effectively support farmers who conserve and generate crop diversity (Andersen, 2005; 2007).

Intellectual property rights have been a recurrent element in the discussions around the concept of farmers' rights. The limitations to use, save, duplicate and exchange plant varieties protected by intellectual property rights, the lack of recognition or compensation for farmers when new products based on their traditional varieties and ancestral knowledge are subject to property rights, the incapacity of the current intellectual property system to adequately protect farmers' varieties and knowledge as well as innovations generated at the community level, are some of the issues that are commonly raised when dealing with the protection of farmers' rights (The Crucible Group, 1994; Leskien and Flitner, 1997; Correa, in press).

Some national laws have attempted to conciliate the different stakeholders' interests with regard to intellectual property protection by combining UPOV-style protection of new plant varieties and a *sui generis* protection of farmers' varieties. Examples of this are the Thailand Plant Varieties Protection Act 1999, the Indian Protection of Plant Varieties and Farmers' Rights Act 2001, and the Malaysian Protection of New Plant Varieties Act 2004. However, the success of such laws in achieving crop diversity conservation and farmers' rights protection is questionable. There is also a great deal of opposition to the belief that conferring private rights to farmer varieties would be beneficial to farmers and farmer communities (Srinivasan, 2003; Eyzaguirre and Dennis, 2007). Jaffe and Van Wijk (1995, p.76) argue that the introduction of plant variety protection causes a change of principle: "When farmers start to use protected varieties, their natural right of seed saving becomes a legal right, or even less, a "privilege." Such a legal right is subjected to political decision–making and possibly prone to restrictions in the future."

Registers of traditional varieties have been promoted by a few national and local governments to help advance the realization of farmers' rights in different ways (Table 1). The registries document and perpetuate traditional knowledge related to the use of crop diversity and have been used to create a sense of ownership over traditional varieties and empower local communities with regards to local activities oriented to the conservation and sustainable use of traditional varieties (Lopez Noriega, in press;Aboagye, 2007). In addition, they have worked as defensive publications and prevent the misappropriation of farmers' genetic resources by acting as a record of the farmer varieties found within the community together with descriptive agronomic, adaptive, quality and other use traits. Examples of local registers can be found in several communities in Nepal (Subedi *et al*., 2005; Sthapit and Quek, 2005). The government of Peru maintains a national register of traditional varieties of potato, and several regional governments in Italy support regional databases of ancient varieties (Lopez Noriega, in press; Ruiz, 2009). In some cases, the registers or databases constitute the basis for the government to provide direct support to the farmers who cultivate traditional varieties. In Hungary, a list of locally-grown traditional varieties targeted for protection is published as an annex to a law, with mechanisms developed for adding new varieties to the list. Farmers who grow crops from the list can receive subsidies, on the condition that they provide a prescribed quantity of seeds to others interested in the growing of the same crop (Mar, 2002, Bela *et al*., 2006.).

Another important aspect of Farmers' Rights, as pointed out by the International Treaty on Plant Genetic Resources for Food and Agriculture,[2] e.g., the farmers' involvement in decision-making processes dealing with plant genetic resources. In reality, due to the complex nature of the trade-offs that genetic resource policies have to address, their development and implementation require the involvement of as many stakeholders as possible (Wale *et al*., 2008). For this reason, innovative governance methods that facilitate communication and understanding among all the actors involved and between science and policy need to be tested and eventually adopted. To a great extent, the local farmers' ability to express themselves in participatory decision-making is linked to the existence of strong and efficient civil society organizations such as farmers' associations representing their interests (Lapena, 2008).

V. BENEFITING FROM THE USE OF LOCAL CROP GENETIC DIVERSITY

Benefits from the use of local crop genetic diversity may come from its current use value, derived from the consumption of a good or service by an individual or a community. Benefits may come from its options value, or the value associated with retaining an option to a good or service in the future. Finally, a resource may be valued for its existence, unrelated to any use of the resource and/or its bequest value, the altruistic value that the individual or community is concerned that the resource should be available to others in the current or future generation (Smale, 2006; Bateman *et al*., 2002). Enhancing the benefits for farmers of local crop diversity means enhancing the net benefits, as there also could be costs to farmers associated with any benefit generating option (Sthapit *et al*., 2008b). This involves ensuring that appropriate incentives for creating and sharing benefits with farmers are developed and that unnecessary or unintended barriers to the flow of benefits to the farmer are not created through the introduction of taxes and subsidies (Bragdon *et al*., 2009).

There are many ways which farmers can derive greater benefits from the traditional crop varieties they manage. The success of these involves *inter alia* supporting local institutions, enhancing collective action and property rights, and enabling farmers to participate and lead the decision making process to the appropriate action and its implementation.

A. Market-Based Actions and Incentives

Markets involve the exchange of goods and services between participants, and as such constitute one of the principal social arenas structuring farmers' management decisions about diversity (Smale, 2006). The market value of agricultural production can be increased through development of new markets, improved marketing, value addition, high value product differentiation; improved processing equipment adapted to diversified

---

[2] The International Treaty on Plant Genetic Resources for Food and Agriculture was adopted by the FAO General Assembly in 2001 and entered into force in 2004. Today, 112 countries and the European Union are parties to the Treaty. Its objectives are the conservation and sustainable use of plant genetic resources for food and agriculture, and the equitable sharing of the benefits arising out of their use, in harmony with the Convention on Biological Diversity. Parties to the Treaty recognize their responsibility for realizing Farmers' Rights under Article 9 of the Treaty.

raw materials, and building trust among market chain actors (Kontoleon *et al*., 2007; Lipper *et al*., 2010; Di Falco and Perrings, 2006; Giuliani, 2007; UNORCAC, 2008; Figure 1: 4a; Table 1).

Agricultural communities interact with markets directly and indirectly on a variety of scales, from household to global. The steady integration of traditional farming regions into wider national and international market relationships is a dominant trend of the last half-century. Pascual and Perrings (2007) reviewed the influence, at the micro-scale (household, family farm) and meso- and macro- scale (national and international policies), of economic and institutional failures that have systematically distorted farm-level decisions to conserve agricultural biodiversity. These include agricultural production subsidies,[3] tax breaks, and price controls (Tilman *et al*., 2002; Kontoleon *et al*., 2007; Kitti *et al*., 2009).

Several market practices have been tested and put in place to create incentives for agricultural biodiversity conservation. "Fair trade" for "free trade" are market schemes that support and advocate replacing millions of dollars in aid by paying a decent price for the products purchased from poorer countries and giving producers in those countries an opportunity to take care of their own production environment (Kitti *et al*. 2009; Kesavan and Swaminathan, 2008; Renard, 2003). Price premiums that represent true costs of production have been studied to understand how they can provide an incentive to conserve agricultural biodiversity and, at the same time, to create benefits for poor farmers (Kitti *et al*., 2009; Perfecto *et al*., 2005; Smith *et al*., 2008). Product labeling can provide consumers with important information not only on food quality, but about the conditions under which the commodity was produced (Swallo and Sedjo, 2000; Giuliani, 2007). This labeling practice includes various geographical identification procedures (Ramakrishnappa, 2006; Garcia *et al*., 2007; Nagarajan, 2007; Salazar *et al*., 2007; Ori-Gin, 2010).

Among other factors, creation of appropriate market conditions depends on the provision of accurate and credible information (Pascual and Perrings, 2007, Lipper *et al*., 2010; FAO, 2007; Okwu and Umoru, 2009; Bela *et al*., 2006). Many developing country farmers are aware of market prices before participating in the market, obtaining information most often from neighbors, followed by village traders, the mass media, and Extension agents (Nagaranjan *et al*., 2009). The increased use of mobile and fixed phones has improved the flow of price information among markets for small scale farmers (Nagaranjan *et al*., 2009). Groups working with rural poor communities in India are supporting local market intelligence systems for small-scale farmers in order to improve the availability of data on demand and supply, production capacity and market prices (Kesavan and Swaminathan, 2008). In some cases, creating stable markets for diverse varieties sold as raw agricultural products may not be a valid option although it may be possible to enhance the benefits to farmers of local varieties by processing them for specific markets (Kruijssen *et al*., 2009). This would involve having processing equipment that can be used with diverse raw materials (Finckh, 2008).

Choice models were originally developed by economists during the 1970s to explain patterns of adoption of "green revolution" crop varieties by farmers in Asia and other regions (Smale, 2006). Subsequent researchers applied and refined revealed preference models to identify why many smallholder farm households continue to grow traditional crop varieties even in the presence of agricultural development and widely available improved varieties (Brush *et al*., 1992; Meng *et al*. 1998; Smale *et al*., 2001; Van Dusen 2006; Gauchan *et al*., 2006). Recent studies have shown that although greater on-farm diversity can increase the likelihood that a household will sell traditional varieties, high levels of diversity on farm may not be reflected in local markets (Edmeades and Smale, 2009). Diversity on-farm was reported to be a necessary condition for market involvement, both in terms of the decision to participate and the richness of traditional varieties sold. But this does not guarantee that on-farm diversity will lead to market sales or diversity at the point of sale (Edmeades and Smale, 2009).

Changes in markets linked to infrastructure and rural development may trigger the erosion of traditional crop varieties, both directly and indirectly. For instance, a new paved road that reaches a previously isolated farm community can help farmers to replace local varieties with improved seeds available in more distant markets. The same road can also enable farm households to substitute newly available goods or services for those previously supplied by diverse varieties (Smale and King, 2005). However, improved access to a greater number of markets can also provide potential incentives for farmers to retain crop diversity, such as when demand for unusual heirloom or niche market varieties exists among urban residents or other consumers (Lee, 2005; Irungu *et al*., 2007; Giuliani, 2007; Van Dusen, 2006; Gauchan and Smale, 2003; Rana, 2004; Gruere *et al*., 2007; Ramirez *et al*., 2009; UNORCAC, 2008).

Assisting smallholder groups to produce together and expand niche markets, will include such activities as educating consumers about the values of diverse varieties, providing better packaging (Gruere *et al*., 2007; Devaux *et al*., 2006) and offering credit provisions to support transportation costs (Lee, 2005; Almekinders *et al*., 2010). In the best of cases, niche markets might be useful for traditional varieties that are also "best fit" to particular ecosystems, such as particular traditional varieties shown to grow well on swampy soil or on poor upland soils (Gauchan and Smale, 2003; Rana, 2004; Gruere *et al*., 2007). Marketing social-cultural aspects of traditional varieties for particular culinary aspects and associated ethnic identity have also been used to create niche markets (Gruere *et al*., 2007; Ramirez *et al*., 2009; Williams, 2009; Sthapit *et al*., 2008a).

---

[3] OEDC developed countries spend approximately US$225 billion annually on agricultural subsidies for their own producers, between one-fourth and one-third the global value of agricultural production in 2000.

Econometric methods have been used to test the effects of crop genetic diversity on expected crop yields and yield variability as well as the probability of crop failure, given levels of pesticide applied (Di Falco and Chavas, 2007). The work has shown that when pesticide use is low crop genetic diversity reduces yield variance, but when pesticide use is high the effect of the crop biodiversity on yield variance is not significant. Indicating that crop genetic diversity is acting as a substitute for pesticides.

Value chain analysis has been used by economists to identify bottlenecks to obtaining increased value from traditional varieties and to map out the relations among actors and flows of crop genetic resources (Andersen *et al*., 2010; Giuliani, 2007; Kruijssen *et al*., 2009). The analysis has shown that stakeholder meetings provide a forum for collecting crucial information about the market chain as the meetings involve as many actors as possible: producers and traders, cultivation experts, NGOS, and representatives of relevant ministries (Giuliani, 2007). These meetings help to design joint ventures with private sector entities. They also create reputation and trust in the areas of quality and prices among farmers, food manufacturers, retailers, NGOs, community-based and government organizations, important in reducing transaction costs (Lipper *et al*., 2010; Almekinders *et al*., 2010; Smith *et al*., 2008) (Table 1). Retailers and other intermediaries are important sources of seed inputs and credit for farmers (Almekinders *et al*., 2010; Giuliani, 2007; Lipper, 2010). They facilitate the flow through the chain by storing, transporting, and reselling seeds and can respond to seed demands from different regions at different planting times.

The role of local markets in seed provision, particularly of traditional varieties has been the subject of a number of important recent studies. Local markets can be more effective in promoting seed movement than specialized traders who may overlook locally sourced seed (Dalton *et al*., 2010). In the case of traditional crop varieties, seed and grain markets are usually the same and the availability and identification of materials that will be used as seed, with information on the desired production and consumption traits may be difficult (Lipper *et al*., 2010). Some studies have suggested that local seed supply channels cannot be enhanced unless they are separated from grain supply channels (Nagarajan and Smale, 2007; Smale *et al*., 2010; Almekinders *et al*., 2010). Enhancing local seed supply channels may involve, for example, developing mechanisms for production and trade of truthfully labeled or quality-declared seed by farmer organizations with building collective action groups that screen and value seed. Certifying the sellers rather than seed may also be an option. Current examples are Producer Marketing Groups (PMGs) in Kenya (Audi *et al*., 2010) and Quality Declared Seeds in Tanzania where small scale farmers are registered to produce seed for local sale and are provided with vendor certification (FAO, 2006b: Granquist, 2009) (Table 1). Smale *et al*. (2010), nevertheless, caution against the formalization of the informal markets in Mali. They suggest that this development could have negative effects on women who would lose the little control they now exert over the grain resources unless they were trained about seed and linked to seed producer groups. It might be more appropriate to develop regulations that shorten the process of certifying seeds or that focus on seed quality rather than seed purity (Lipper *et al*., 2010).

B. Non-Market-Based Actions and Incentives

The full value of agricultural biodiversity and its services is not captured by the market because of a failure to internalize external costs (Thies, 2000). Crop biodiversity has socio-cultural, insurance and option values, that will be underestimated if left to the market (Pascual and Perrings, 2007; Smale, 2006). These different values of traditional varieties may to some extent be realized through non-market incentives (Figure 1: 4*b*;Table 1). They can be realized, for instance, by improving public awareness about sociocultural values of traditional varieties (Birol *et al*., 2007), by providing information on the substitution value of traditional variety diversity for fertilizer and pesticides (Di Falco and Perrings, 2007), moral suasion, regulation and planning, by preventing specific land management practices such as low input zones (Pascual and Perrings, 2007), by designing agroecological parks or agrotourism zones (Ruiz, 2009; Ramirez *et al*., 2009; Ceroni, *et al*., 2007). Other possibilities include compensating farmers for their conservation functions through payment for environmental services (FAO, 2007; Brussaard *et al*., 2010) or by supplying insurance functions and option values (Bragdon *et al*., 2009). Insofar as they exist, the enforcement of Farmers' Rights, and the adaptation and enforcement of intellectual property law could also play a role.

Methods to assess the non-market value of public goods can be divided into two categories (Birol *et al*., 2007): 1) choice experiment studies (or direct methods) that use stated preference (willingness to pay/accept) to investigate the public's valuation of agri-environmental schemes and crop genetic reources (Campell *et al*., 2006; Birol and Ryan-Villalba, 2009); and, 2) hedonic analysis (or indirect methods) that use revealed preference (market information) to estimate the value of attributes of crop genetic resources (Van Dusen and Taylor, 2005; Edmeades, 2006; Edmeades and Smale, 2009). Birol *et al*. (2007) reviewed the different models and experimental data for obtaining not-market values of biodiversity resources. They combined choice experimental data with farm household data and concluded that welfare measures derived form non-market public goods could be more accurate when the methods are combined. Welfare measures (willingness to accept compensation) can be calculated for different agrobiodiversity attributes within the farmers' production system and for the services provided by traditional varietal diversity. These methods have helped to identify least cost agri-environmental schemes that can encourage farmers to undertake home gardens and on-farm management practices to support the conservation and use of traditional varieties (Birol *et al*., 2006; 2007; 2009; Poudel and Johnsen, 2009).

Diversity, in the form of traditional varieties, has also been valued as a deliberate strategy for managing abiotic and biotic pressures in labor-intensive production systems with low levels of chemical inputs (Edmeades *et al*., 2006; Waage *et al*., 2008). Low chemical input or organic farming with local varieties can promote agro-ecosystem stability and health (Østergård *et al*., 2009). Other studies have been used to account for substitution value that traditional varietal diversity may give for pesticide inputs using a damage-abatement framework. These models value the effect of crop varietal diversity not only for the yield effect but also for the damage abatement effect of crop genetic choices as a substitute for pesticide application (Oude and Carpentier, 2001). In this context, it is also worth noting that pesticide manufacturers probably do not pay the full cost of the adverse affects that pesticides have on the environment of human health (Pretty, 2008; Pingali and Roger, 1995).

There are several examples across the world of countries and institutions implementing mechanisms to capture the non-market value of local agricultural biodiversity (Table 1). Environmentally Sensitive Areas (ESAs) in Hungary are a window for promoting organic farming, which could include the use of traditional crop varieties (Bela *et al*., 2006). In Poland semi-subsistence farms are often regarded as a major obstacle to development. However, Siudek (2008) notes that expanding farm businesses to include agrotourism in rural areas of Poland would have the potential to reverse negative economic trends. Agricultural biodiversity for recreation (Ceroni *et al*., 2007; UNORCAC, 2008) includes agrotoursim zones established in Peru (Ruiz, 2009) and agrobiodiversity botanical gardens in Ecuador (Williams and Ramirez, 2006). These emphasize both traditional crop diversity and cultural identity and are a means to share benefits with local farming communities.

Bela *et al*. (2006) have suggested that there is a need to improve communication among stakeholders to understand trade-offs between public attributes and profitability. Advertising campaigns could be used, for example, to change norms on nutrition and taste and or try to reduce the use of chemical inputs. Education on the value of increasing use of traditional varieties can be part of these campaigns. Modification of existing primary and secondary school curricula to include agricultural biodiversity as an adaptive resource in biology courses is another method of introducing new ideas into the education system (Ramirez *et al*., 2009; UNORCAC, 2008) (Table 1).

Case studies compiled in the context of the Convention on Biological Diversity indicate that empowerment and benefit-sharing with farmers and farming communities will only take place if additional measures accompany activities related to access and benefit-sharing (Regine, 2005; Convention on Biological Diversity, 2010). National laws on access to genetic resources, intellectual property and bio-safety need to form part of the legal landscape that supports the use of traditional varieties. This includes advocating that local and national governments integrate biodiversity, including agricultural biodiversity, into their legislation on environmental impact assessment of projects, policies, plans and programs as a method for informing decision-making with regard to agrobiodiversity maintenance and use (Slootweg *et al*., 2006; Wale, in press).

Participatory plant breeding has been shown to help enable farmers to influence the development of materials and technologies in ways that are informed by their specific needs, agro-ecological environments and cultural preferences (Halewood *et al*, 2007; Gyawali *et al*., 2007; in press). The Thai Plant Variety Protection Act is one example of a law that includes a benefit-sharing scheme by which those who are granted plant breeders' rights must pay part of the monetary benefits gained through the commercialization of the variety to a common fund which will support Thai small farmers who conserve and use crop diversity. The practical implementation of the law has been very challenging and the plant variety fund is still empty (Gagne and Ratanasatien, in press). Benefit-sharing policies must combine different approaches; the reality shows that conservation of crop diversity on farm cannot rely only on levies on plant breeders' royalties (Srinivasan, 2003).

It has been argued that true benefit-sharing involves developing mechanisms that support communities and their farming systems and thus agricultural techniques that conserve local agricultural biodiversity. Farmers' Rights implies the development of some means of ensuring benefits flow to farmers and farming communities either through an ownership approach or a stewardship approach[4] (Farmers' Rights, 2010). In this context, creating incentives and removing disincentives to enable farmers to continue their work as stewards and innovators of agricultural biodiversity need to be part of any benefit-sharing mechanism (Bragdon *et al*., 2009). Currently, disincentives to the maintenance of traditional varieties may be associated with various aspects or consequences of agricultural development strategies such as 1) alterations in land tenure systems that threaten the survival of traditional farming communities; 2) subsidy schemes that promote exclusive adoption of uniform agricultural productions; 3) research programs that neglect traditional varieties and their associated knowledge and uses; and 4) food standards that limit entry of traditional farmers' varieties and products into markets.

C. Strengthening Local Institutions and Farmer Leadership

All approaches or activities to enhance benefits to farmers rely on building up social capital, or the ability of men and women farmers to develop and use social networks (Figure 1: 4*c*). Social networks help farmers to obtain access to credit as well as information and knowledge about new options and practices. Furthermore, these networks expand choices available to each household member (Pretty, 2002; Bantilan and Padmaja 2008). Building social capital includes developing appropriate

---

[4] The ownership approach refers to the right of farmers to be rewarded for genetic material obtained from their fields and used in commercial varieties and/or protected through intellectual property rights. The stewardship approach refers to the rights that farmers must be granted in order to enable them to continue as stewards and as innovators of agro-biodiversity. Benefit-sharing is most promising when the point of departure is the farming communities that actually contribute to the maintenance of plant genetic diversity benefits (Regine, 2005).

collective management practices, which are understood as the voluntary action that is taken by a group to achieve common interests and property regimes (Meinzen-Dick and Eyzaguirre, 2009; Eyzaguirre and Evans, 2007). Through collective action members of the group may act directly on their own or through an organization, such as deciding on and observing rules for use or non-use of a resource through coordinated activities across individual farms. Property rights involve the "the capacity to call upon the collective to stand behind one's claim to a benefit stream" (Bromley, 1991). Interventions to strengthen the property rights of individuals or groups to help them participate in collective activities can improve their bargaining positions (Eyzaguirre and Evans, 2007). This may involve the development of institutional mechanisms that local participants can use to organize themselves, such as through special districts, private associations, and local/regional governments (Meinzen-Dick and Eyzaguirre, 2009) and better link them to policy institutions (Pretty, 2008).

Combinations of farmer innovation and empowerment, the transformation of local government staff, and the establishment of new farmer–governed local institutions that have equitable links to the private sector have resulted in successful collective action for equitable management and use of traditional crop varieties (Friss-Hansen, 2008; Pretty 2008; Swaminathan, 2003; UNORCAC, 2008) (Table 1). Pimbert *et al.* (2010) discusses citizen juries formed by farm leaders, progressive researchers, and NGO technicians to evaluate, deliberate, and publicly address the equity and sustainability of conventional research systems and initiatives in West Africa. Collective action is important in enabling farmers to address market imperfections and transaction costs, such as in surmounting information, credit and marketing constraints. Such institutions support farmer unions and cooperatives for educating farmers in production and marketing, assisting with price negotiations, collecting land taxes, and information sharing (Caviglia and Kahn, 2001).

Diversity field fora (Smale *et al*., 2008), which bear some similarity to farmer field schools (see Van der Berg and Jiggins, 2007), are becoming a new institution in West Africa which can strengthen the capacity of farmers to analyze, manage and improve their own crop plant genetic resources (Bioversity International, 2008). In diversity field flora, farmers acquire both knowledge and leadership skills through experiments that are designed and conducted by the farmers with technical support from project staff, to better manage and benefit from their crop genetic resources (Bioversity International, 2009; Smale *et al*., 2008; Jackson *et al*., 2010). The community-based biodiversity management (CBM) approach, developed in Nepal and now being tested in South and Southeast Asia, is a similar multi-step process that focuses specifically on strengthening the local decision-making and governance capacity of communities to utilize agricultural biodiversity (Sthapit *et al*., 2006a; De Boef *et al*., 2007). Collective action is also supported when participatory plant breeding is not limited to the development of varieties for a specific area, but becomes part of integrated community-based biodiversity management activities (Sthapit *et al*., 2008b).

It has been argued that agricultural policies are required that build human capital (Neuchatel Group, 2007; Smale *et al*., 2006). Policies that support inclusive agricultural extension or advisory services need to go hand in hand with the process of strengthening local institutions. Extension services have to be more responsive to the needs of all farmers, including women and those who are poor and marginalized (Neuchatel Group, 2007; Smale *et al*., 2006). This is likely to involve paying increased attention to contextual factors in the design and implementation of agricultural extension service programs. In addition to the characteristics of the local communities, the types of farming systems and the degree of market access are examples of important contextual factors that need be be taken into account (Birner *et al*., 2010). In the same way it has been suggested that agricultural policies need to be more gender sensitive and designed to empower women by providing knowledge and ensuring access and control of resources toward achieving food security (MEA, 2005). Women have multiple responsibilities within the household and communities but are often ignored at all levels of decision-making.

Most studies agree on the need to improve trust and mutual understanding across different actors and institutions (Kruijssen *et al*., 2009). These studies emphasize the need for reciprocity, obligations, and mutually agreed upon rules, which are structured and connected through groups and networks (Cramb and Culasero, 2003; Pretty, 2008). Cultural institutions, such as weddings and tea houses, are places of trust where information on traditional crop diversity is exchanged and which could be linked to wider support networks (Van Dusen *et al*., 2006). There is potential for local institutional support and capacity building to link individuals of different networks together through a neutral party (NGO or other organization) or to both build smaller networks that could be linked to help diffuse innovations and messages (Granovetter, 1973). Resilience is built into agroecological production systems through supporting institutions and social-ecological networks that create flexibility in problem solving and that can balance power among interest groups (Folke *et al*., 2002; Walker *et al*., 2002; 2010). These many different types of networks can be strengthened by linking them to community-based seed production groups and to participatory plant breeding schemes so as to capitalize on natural pathways of seed flow. Networks can help demystify laboratory-based technologies (Kesavan and Swaminathan, 2008), provide technology empowerment, and support literacy training, to enable farmers to have more control over their resources (Swaminiathan, 2003). These can be supported by knowledge empowerment actions that take advantage of the new information and communication technology (Kesavan and Swaminathan, 2008).

VI. CONCLUSIONS

Over the last two decades a substantial body of information has developed on the continuing maintenance and use of traditional varieties by small-scale farmers around the world.

Farmers appear to find that diversity, in the form of traditional varieties of both major staples and minor crops, remains important to their livelihoods, despite earlier expectations that these varieties would rapidly disappear from production systems.

No doubt the arguments about long-term trends with respect to the continued use of traditional varieties will continue. However, there are a number of reasons for thinking that these varieties will continue to play an important role for many crops in a wide variety of production systems in the future. In addition to the reasons such as adaptation to marginal and low input agriculture, stable performance, and the socioeconomic conditions of many small-scale farmers—who, as Lipton (2006) noted, make up 45–60% of the rural poor—already mentioned in the Introduction, farmers around the world are using traditional varieties to help cope with climate change (Platform for Agrobiodiversity Research, 2010). The growing concern with developing more sustainable production systems and reducing dependence on chemical inputs is also likely to favour the maintenance and use of traditional varieties.

In these circumstances it seems important not only to understand better the nature and contribution of traditional varieties to the production strategies of rural communities around the world, but also ways in which they are maintained and managed. This can help in the development of ways of improving the use of these varieties and their contribution to rural livelihoods. As shown in this review, there is a rich and growing body of information on traditional varieties, and on the problems and benefits associated with their maintenance and use. The review has also demonstrated the importance of work that adopts a multidisciplinary approach and emphasizes working with farmers in collaborative ways. There remain clear gaps in our knowledge. There is still a need to develop better indicators and ways of monitoring diversity that are adapted for the use of farmers, communities, and scientists. Molecular methods, which can now provide significant additional insights into the extent and distribution of diversity and on the ways in which it is correlated with important social, environmental, and management variables have yet to be undertaken on the scale needed except perhaps for sorghum and pearl millet in Africa (e.g. Barnard *et al*., 2008; Bezancon *et al*., 2009; Busso *et al*., 2000; Deu *et al*., 2008; Sagnard *et al*., 2008; Allinne *et al*., 2008). With the rapid improvements in methods over the last decades this is now possible on the required scale.

While each situation may appear to be unique with respect to the amount of diversity present in the system, its distribution and the associated biological, environmental, socioeconomic, and cultural characteristics, it is possible to recognize general properties which can be used to ascertain the sorts of activities that farmers, and those working with them, may find useful in identifying ways in which traditional varieties can both be maintained and contribute to improved livelihoods. The heuristic framework presented here provides a number of overlapping approaches and entry points for such activities. At present this probably should be regarded very much as "work in process" as it is likely to be amended as further information becomes available. However, even at this stage, it is possible to draw some general conclusions based on its application. Firstly, it is essential to develop an appropriate understanding of the extent and distribution of diversity in a system and of how it is maintained through local institutions and practices. Secondly, the analysis is likely to lead to the identification of a number of complementary supporting actions. Thirdly, the success of any actions will depend centrally on local knowledge, the strength of local institutions and the leadership of farmers and communities.

ACKNOWLEDGMENTS

The authors thank Daniela Horna, Susan Bragdon, and Louise Jackson for their critical review of this document. We thank Chiara Boni for her substantial contribution toward the organizing and editing the extensive list of references cited here, and Marleni Ramirez, David Williams and Muhabbat Turdieva for providing references on related work in Latin America and Central Asia. The idea for this paper came from discussions with Christina Grieder and Jean-Bernard Dubois of the Swiss Agency for Development and Cooperation (SDC) who several years ago asked us to tell them what concrete conservation and development actions could be taken based on the research that they supported the last fifteen years to "Strengthen the Scientific Basis of *In Situ* Conservation of Agricultural Biodiversity On-Farm."

REFERENCES

Abate, T., van Huis, A., and Ampofo, J. K. O. 2000. Pest management strategies in traditional agriculture: An African perspective. *Ann. Rev. Entomol.* **45:** 631–659.

Aboagye, L. M. 2007. Strategies for sustainable conservation and use of legume genetic resources in Ghana. *Ghana J. Sci.* **47:** 59–67.

Adato, M., and Meinzen-Dick, R. (Eds.) 2007. *Agricultural Research, Livelihoods, and Poverty: Studies of Economic and Social Impact in Six Countries.* International Food Policy Research Institute (IFPRI), Washington, DC 2006, USA.

Adhikari, A., Rana, R. B., Gautam, R., Subedi, A., Upadhyay, M. P., Chaudhary, P., Paudel, I., Rijal, D., and Sthapit, B., 2006b. Diversity fair: Promoting exchange of knowledge and germplasms. **In:** *Good Practices: On-farm management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K. and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Adhikari, A., Upadhyay, M. P., Joshi, B. K., Rijal, D., Chaudhary, P., Paudel, I., Baral, K. P., Pageni, P., Subedi, S., and Sthapit, B. 2006a. Multiple approach to community sensitization. **In:** *Good Practices: On-farm management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K., and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Agbaje, G. O., Ogunsumi, L., Oluokun, J. A., and Akinlosotu, T. A. 2005. Survey of yam production system and the impact of government policies in southwestern Nigeria. *J. Food Agric. Environ.* **3:** 222–290.

Aguilar-Støen, M., Moe, S. R., and. Camargo-Ricalde, S. L. 2009. Home gardens sustain crop diversity and improve farm resilience in Candelaria Loxicha, Oaxaca, Mexico. *J. Hum. Ecol.* **37**(1): 55–77.

Aharoni, A., and Vorst, O. 2001. DNA microarrays for functional plant genomics. *Plant Mol. Biol.* **48:** 99–118.

Allinne C., Mariac, C., Vigouroux, Y., Bezancon, G., Couturon, E., Moussa, D., Tidjani, M., Pham, J. L., and Robert, T. 2008. Role of seed flow on the pattern and dynamics of pearl millet (*Pennisetum glaucum* [L.] R. Br.) genetic diversity assessed by AFLP markers: a study in south-western Niger. *Genetica* **133:**167–178.

Almekinders, C. J. M., Cavatassi, R., Terceros, F., Romero, R. P., and Salazar, L. 2010. Potato seed supply and diveristy: dynamics of local markets of Cochabamba province, Bolivia – a case study. **In:** *Seed Trade In Rural Markets: Implications for Crop Diversity and Agricultural Development*. pp. 75–94. Lipper, L., Anderson C. L., and Dalton, T. J., Eds., United National Food and Agricultural Organization (FAO), Italy.

Almekinders, C. J. M., Louwaars, N. P., and de Bruijn, G. H. 1994. Local seed systems and their importance for an improved seed supply in developing countries. *Euphytica* **78:** 207–216.

Almekinders, C., Molina-Centeno, J., Herrera-Torrez, R., Merlo-Olivera, S. L., González-Suárez, J. M., and García-Carrasco, J. 2006. Learning experiences obtained from the development of bean varieties through participative breeding in Northern Nicaragua. *Agron. Mesoam.* **17**(3): 327–336.

Almekinders, C. J. M., Thiele, G., and Danial, D. L. 2007. Can cultivars from participatory plant breeding improve seed provision to small-scale farmers? *Euphytica* **153:** 363–372.

Amend, T., Brown, J., Kothari, A., Phillips, A., and Stolton, S. 2008. Protected landscapes and agrobiodiversity values. **In:** *Protected Landscapes and Seascapes* Volume 1. Amend, T., Brown, J., Kothari, A., Phillips, A. and Stolton, S., Eds., IUCN & GTZ, Kasparek Verlag, Heidelberg.

Andersen, R. 2005. *Results of an International Survey on Farmers' Rights*. The Fridtjof Nansen Institute, Norway.

Andersen, R. 2007. *Protecting Farmers' Rights in The Global IPR Regime. Challenges and options for developing countries.* SAWTEE Policy Brief No. 15.

Andersen, E., Kantor, P., and Sim, A. 2008. *Microcredit, Informal Credit and Rural Livelihoods: A Village Case Study in Bamyan Province*. Afghanistan Research and Evaluation Unit. Afghanistan. http://www.ecoi.net/file_upload/1227_1214850224_microcredit-bamyan-cs.pdf Accessed 28 May 2010.

Anderson, C. L., Lipper, L., Dalton, T. J., Smale, M., Hellin, J., Hodgkin, T., Almekinders, C., Audi, P., Bellon, M. R., Cavatassi, R., Diakite, L., Jones, R., Oliver King, E. D. I., Keleman, A., Meijer, M., Osborn, T., Nagarajan, L., Paz, A., Rodriguez, M., Sibide, A., Salazar, L., van Heerwaarden, J., and Winters, P. 2010. Project methodology: using markets to promote the sustainable utilization of crop genetic resources. **In:** *Seed Trade in Rural Markets*. pp. 31–48, Lipper, L., Anderson, C. L., and Dalton, T. J., Eds., Earthscan, London, U.K.

Arias, L. 2004. *Diversidad Genetica y Conservación in Situ de los Maices Locales de Yucatan, México* [Genetic Diversity and In Situ Conservation of Local Maize in Yucatán, Mexico]. PhD thesis, Instituto Tecnologico de Merida, Yucatán, México (in Spanish), Merida, Mexico.

Arias, L., Chávez, J., Cob, B., Burgos, L., and Canul, J. 2000. Agromorphological characters and farmer perceptions: Data collection and analysis. Mexico. **In:** *Conserving Agricultural Biodiversity in Situ: A Scientific Basis for Sustainable Agriculture.* pp. 95–100. Jarvis, D. Sthapit, B.. and Sears, L. Eds., International Plant Genetic Resources Institute, Rome.

Arndorfer, M., Kajtna, B., Vorderwülbecke, B., and Dixon, G. R. 2009. Integrating ex situ and on-farm conservation approaches in the management of local vegetable diversity in Austria. *Acta Hortic.* **817:** 333–340.

Asfaw, A., Almekinders, C., Getahun D., and Fistum, A. 2007. Bean seed flow and exchange networks in Southern Ethiopia. *Seed Info* **33:** 14–17.

Audi, P., Nagrajan, L., Jones, R.. and Ibrahim, M. S. 2010. Pigeonpea seed supply and diveristy: a case study of local seed markets in Makueni District, Eastern Kenya. **In:** *Seed Trade in Rural Markets: Implications for Crop Diversity and Agricultural Development.* pp 95–123. Lipper, L., Anderson, C. L.. and Dalton, T.J., Eds., United National Food and Agricultural Organization (FAO), Italy.

Aw-Hassan, A., Mazid, A., and Salahieh, H. 2008. The role of informal farmer-to-farmer seed distribution in diffusion of new barley varieties in Syria. *Exp. Agric.* **44**(3): 413–431.

Badstue, L. B., Bellon, M., Berthaud, J., Juarez, X., Manuel-Rosas, I., Solano, A. M., and Ramirez, A. 2006. Examining the role of collective action in an informal seed system: A case of study from the Central Valleys of Oaxaca, Mexico. *Hum. Ecol.* **34:** 249–273.

Badstue, L. B., Bellon, M., Berthaud, J., Ramirez, A., Flores, D., and Juarez, X. 2007. The dynamics of seed flow among maize growing small-scale farmers in the Central Valleys of Oaxaca, Mexico. *World Dev.* **35**(9): 1579–1593.

Badstue, L. B., Bellon, M., Juárez, X., Manuel, I., and Solano, A. M. 2002. Social relations and seed transactions among small-scale maize farmers in the Central Valleys of Oaxaca, Mexico: preliminary findings. **In:** *CIMMYT Economics Working Paper* 02–02. CYMMIT, Texcoco, Mexico.

Bajracharya, J., Rana, R. B., Gauchan, D., Sthapit, B.R., Jarvis D.I., and Witcombe, J. R. 2010. Rice landrace diversity in Nepal. Socio-economic and ecological factors determining rice landrace diversity in three agro-ecozones of Nepal based on farm surveys. *Genet. Resour. Crop Ev.* DOI 10.1007/s10722-010-9544-x (*published on line 19 March 2009*).

Bajracharya, J., Steele, K. A., Jarvis, D. I., Sthapit, B. R., and Witcombe, J. R. 2006. Rice landrace diversity in Nepal: variability of agromorphological traits and SSR markers in landraces from a high-altitude site. *Field Crop Res.* **95:** 327–335.

Bajracharya, J., Steele K. A., Witcombe, J., and Jarvis, D. 2001. A study of genetic relationships in rice (*Oryza sativa* L.) landraces of Jumla using microsatellite DNA markers. **In:** *Abstracts of National Workshop 2001 of the Project "Strengthening the Scientific Basis of in Situ Conservation of Agricultural Biodiversity On-Farm."* pp. 7–8. Sthapit B. R., Subedi, A., Upadhyay, M. P.. and Baniya, B. K., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Ballantyne, P. 2009. Accessing, sharing and communicating agricultural information for development: emerging trends and issues. *Inform. Dev.* **25**(4): 260–271.

Balma, D. B., Dossou, M., Sawadogo, R. G., Zangre, J., Ouédraogo, T., and Jarvis, D. I. (Eds.) 2004. *La Gestion de la Diversité des Plantes Agricoles Dans les Agro-Ecosystemes.* Compte-rendu des travaux d'un atelier abrité par CNRST, Burkina Faso et International Plant Genetic Resources Institute. Ouagadougou, Burkina Faso, 27-28 Décembre 2002. International Plant Genetic Resources Institute, Rome, Italy (in Franch).

Bantilan, M. C. S., and Padmaja, R. 2008. Empowerment through social capital build-up: gender dimensions in technology uptake. *Exp. Agric.* **44:** 61–80.

Baniya, B. K., Tiwari, P. R., Pandey, D., and Bajracharya, J. 2003. Field study of two barley landraces of Jumla. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal. Proceedings of a National Workshop, 24-26 April 2001.* pp. 127–135. Sthapit, B. R., Upadhyay, M. P., Baniya, B. K., Subedi, A.. and Joshi, B. K., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute, Lumle, Nepal.

Baral, K. P., Sapkota, T., Bhandari, B., Adhikari, A., Dewan, S., Pageni, S., Subedi, A., and Upadhyay, M. P. 2006. Rural radio programme: an effective tool for reaching unreachable on biodiversity conservation issues. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* number 17. Sthapit, B. R., Shrestha, P. K. and Upadhyay, M. P. Eds., NARC, LI-BIRD, International Plant Genetic Research Institute and IDRC, Kathmandu, Nepal.

Barnaud, A., Trigueros, G., McKey, D., and Joly, H. I. 2008. High outcrossing rates in fields with mixed sorghum landraces: how are landraces maintained? *Heredity* **101**(5): 445–452.

Barr, A. R. 2009. Marker-assisted selection in theory and practice. pp. 479–518. **In:** *Plant Breeding and Farmer Participation*. Ceccarelli, S., Guimarães, E. P.. and Weltzien, E. Eds., ICRISAT, ICARDA and United National Food and Agricultural Organization (FAO), Rome Italy.

Barry, M. B., Pham, J. L., Noyer, J. L., Courtois, B., Billot, C., and Ahmadi, N. 2007. Implications for *in situ* genetic resource conservation from the ecogeographical distribution of rice genetic diversity in Maritime Guinea. *Plant Genet. Resour.* **5:** 45–54.

Bartlett, A. 2008. No more adoption rates! Looking for empowerment in agricultural development programmes. *Dev. Pract.* **18:** 4–5.

Bateman, I. J., Carson, R. T., Day, B., Hamnemann, W. M., Hanley, N., Hett, T., Jones-Lee, M., Loomes, G., Mourato, S., Ozdemiroglu, E., Pearce, D. W., Sugden, R., and Swanson, J. 2002. *Economic valuation with state preference techniques: A manual*. Edward Elgar, Cheltenham.

Baymetov, K. I., Rajametov, S. N., and Nazarov, P. T. 2009. Raznoobrazie i sokhranenie mestnikh sortov abrikosa v fermerskikh khozyaistvakh. (Diversity and conservation of local varieties of apricot on farms). *Materials of the Republican Scientific-Practical, Conference on "Conservation and Sustainable Use of Biodiversity of Agricultural Crops and Their Wild Relatives"*. Tashkent, Uzbekistan, pp. 15–18 (in Russian).

Beckett, S. J., Fields, P. G., and Subramanyam, B. H. 2007. Disinfestation of stored products and associated structures using heat. **In:** *Heat Treatment for Post Harvest Pest Control.* pp. 182. Tang, J., Mitcham, E., Wang, S., and Lurie, S., Eds., CABI Publishing, Wallingford, UK.

Bela, G., Balazs, B., and Pataki, G. 2006. Institutions, stakeholders and the management of crop biodiversity on Hungarian family farms. **In:** *Valuing Crop Biodiversity, on Farm Genetic Resources and Economic Change.* pp. 251–269. Smale, M., Eds., CABI Publishing, Wallingford, UK.

Bélanger, J., and Johns, T. 2008. Biological diversity, dietary diversity, and eye health in developing country populations: Establishing the evidence-base. *EcoHealth* **5**(3): 244–256.

Belay, G., Tefera, H., Getachew, A., Kebebew, A., and Gizow, M. 2009. Highly client-oriented breeding with farmer participation in the Ethiopian cereal tef (*Eragrostis tef* (Zucc.) Trotter). *Afr. J. Agric. Res.* **3**(1): 22–28.

Belay, G., Tefera, H., Tadesse, B., Metaferia, G., Jarra, D., and Tadesse, T. 2006. Participatory variety selection in the Ethiopian cereal Tef (*Eragrostis tef*. L.). *Expl. Agric.* **42:** 91–101.

Belem, M. O. 2000. Burkina Faso, gender: methods used to create a framework for implementation and management of in situ conservation on-farm. **In:** *Conserving Agricultural Biodiversity in Situ: A Scientific Basis for Sustainable Agriculture*. pp. 72–73. Jarvis, D., Sthapit, B., and Sears, L., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Bellon, M. R. 2004. Conceptualizing interventions to support on-farm genetic resource conservation. *World Dev.* **32:** 159–172.

Bellon, M.R., and Brush, S.B. 1994. Keepers of the maize in Chiapas, Mexico. *Econ. Bot.* **48:** 196–209.

Bellon, M. R., Pham, J. L., and Jackson, M.T. 1997. Genetic conservation: A role for rice farmers. **In:** *Plant Conservation: The in Situ Approach*. Hawkes, J. G., Eds., Chapman & Hall, London, U.K.

Bellon, M. R. ,and Risopoulos, J. 2001. Small-scale farmers expand the benefits of improved maize germplasm: A case study from Chiapas, Mexico. *World Dev.* **29**(5): 799–811.

Bellon, M.R., and Taylor, J.E. 1993. "Folk" soil taxonomy and the partial adoption of new seed varieties. *Econ. Dev. Cult. Change* **41**(4): 763–786.

Belqadi, L. 2003. *Diversité et ressources génétiques de Vicia faba L. au Maroc: variabilité, conservation ex situ et in situ et valorisation*. Doctorat de thèse ès-sciences agronomiques, Institut Agronomique et Vétérinaire Hassan II, Rabat, Morocco (in French).

Bengtsson, J., Ahnström, J., and Weibull, A. C. 2005. The effects of organic agriculture on biodiversity and abundance: A meta-analysis. *J. App. Ecol.* **42:** 261–269.

Benin, S., Smale, M., and Pender, F. 2006. Explaining the diversity of cereal crops and varieties grown on household farms in the Highlands of Northern Ethiopia. **In:** *Valuing Crop Biodiversity*. pp. 78–96. Smale, M., Eds., CABI Publishing, Wallingford, UK.

Bentley, J. W., Tripp, R., and Delgado de la Flor, R. 2001. Liberalization of Peru's formal seed sector. *Agric. Hum. Values* **18:** 319–331.

Benton, T. G., Vickery, J. A., and Wilson, J. D. 2003. Farmland biodiversity: is habitat heterogeneity the key? *Trends Ecol. Evol.* **18**(4): 182–188.

Berg, T. 2009. Landraces and folk varieties: a conceptual reappraisal of terminology. *Euphytica* **166:** 423–430.

Bertuso, A., Ginogaling, G., and Salazar, R. 2000. Community gene banks: the experience of conserve in the Philippines. **In:** *Encouraging Diversity- The conservation and Development Of Plant Genetic Resources.* pp. 117–122. Almekinders, C., and de Boef, W., Eds., Intermediate Technology Publications, London, UK.

Bertuso, A. R., van Treuren, R., van Eeuwijk, F. A., and Visser, L. 2005. Characterization of red rice (*Oryza sativa*) varieties developed under on-farm dynamic management on Bohol, Philippines. *Plant Genet. Resour. Newsl.* **142:** 68–72.

Bezabih, M. 2008. Agrobiodiversity conservation under an imperfect seed system: the role of community seed banking schemes. *Agric. Econ.* **38:** 77–87.

Bezançon, G., Pham, J. L., Deu, M., Vigouroux, Y., Sagnard, F., Mariac, C., Kapran, I., Mamadou, A., Gérard, B., Ndjeunga, J., and Chantereau, J. 2009. Changes in the diversity and geographic distribution of cultivated millet (*Pennisetum glaucum* (L.) R. Br.) and sorghum (*Sorghum bicolor* (L.) Moench) varieties in Niger between 1976 and 2003. *Genet. Resour. Crop Ev.* **56:** 223–236.

Bhandari, B. 2009. *Summer Rainfall Variability and the Use of Rice (Oryza Sativa L.) Varietal Diversity for Adaptation: Farmers' Perceptions and Responses in Nepal.* Master Thesis. CBM Swedish Biodiversity Centre, Uppasala, Sweden.

Bioversity International. 2008. *Manuel de Formation des Fornateurs Sur les Champs de Diversite.* pp. 244. Bioversity International, Rome, Italy (in French).

Birner, R., Davis, K., Pender, J., Nkonya, E., Anandajayasekeram, P., Ekboir, J., Mbabu, A., Spielman, D. J., Horna, D., Benin, S., and Cohen, M. 2009. From best practice to best fit: a framework for designing and analyzing pluralistic agricultural advisory services worldwide. *J. Agric. Educ. Exten.* **15:** 341–355.

Birol, E., Kontoleon, A., and Smale, M. 2007. Assessing the private value of agro-biodiversity in Hungarian home gardes using the data enrichment methods. **In:** *Biodiversity Economics.* pp. 594–622. Kontoleon, A., Pascual, U., and Swanson, T. M., Eds., Cambridge University Press, UK.

Birol, E., and Rayan-Villalba, E. 2009. Estimating the value of milpa diversity and genetically modified maize to farmers in Mexico: a choice experiment approach. **In:** *Agrobiodiversity Conservation and Economic Development.* pp. 247–277. Kontoleon, A., Pascual, U. and Smale, M., Eds., Routledge, UK.

Birol, E., Smale, M., and Gyovai, Á. 2006. Using a choice experiment to estimate farmers' valuation of agrobiodiversity on Hungarian small farms. *Environ. Resour. Econ.* **34:** 439–469.

Bishaw, Z., and Turner, M. 2008. Linking participatory plant breeding to the seed supply system. *Euphytica* **163:** 31–44.

Bishaw, Z., and van Gastel, A. J. G. 2009. Variety release and policy options. **In:** *Plant Breeding and Farmer Participation.* pp. 565–587, Ceccarelli, S., Guimareaes, E. P. and Weltzien, E., Eds., United National Food and Agricultural Organization (FAO), Rome, Italy.

Bisht, I. S., Mehta, P. S., and Bhandari, D. C. 2007. Traditional crop diversity and its conservation on-farm for sustainable agricultural production in Kumaon Himalaya of Uttaranchal state: A case study. *Genet. Resour. Crop Ev.* **54:** 345–357.

Blum, A. 2004. The physiological foundation of crop breeding for stress environments. **In:** *Proc. World Rice Research Conf., Tsukuba, Japan, November 2004*. pp. 456–458. International Rice Research Institute, Manila, Philippines.

Boster, J.S. 1985. Selection for perceptual distinctiveness: evidence from Aguaruna cultivars of *Manihot esculenta*. *Econ. Bot.* **39**(3): 310–325.

Bouzeggaren, A., Birouk, A., Kerfal, S., Hmama, H., and Jarvis, D. I. 2002. Conservation in situ de la biodiversité des populations noyaux de luzerne locale au Maroc. **In:** *La conservation in Situ de la Biodiversité Agricole: Un Défi Pour une Agriculture Durable*. Birouk, A., Sadiki, M., Nassif, F., Saidi, S., Mellas, H., Bammoune, A. and Jarvis, D., Eds., International Plant Genetic Resources Institute, Rome, Italy (in French).

Bouhassan, A., Sadiki, M., and Tivoli, B. 2003a. Evaluation of a collection of faba bean (*Vicia faba* L.) genotypes originating from the Maghreb for resistance to chocolate spot (*Botrytis fabae*) by assessment in the field and laboratory. *Euphytica* **135:** 55–62.

Bragdon, S., Jarvis, D. I., Gaucham, D., Mar, I., Hue, N. N., Balma, D., Collado, L., Latournerie, L., Sthapit, B., Sadiki, M., and N'dungu-Skilton, J. 2009. The agrobiodiversity policy development process: exploring means of policy development to support the on-farm management of crop genetic diversity. *Int. J. Biodivers. Sci. Manage.* **5**:10–20.

Brocke vom, K. A., Christinck, E., Weltzien, R., Presterl, T., and Geiger, H. H. 2003. Farmers' seed systems and management practices determine pearl millet genetic diversity patterns in semiarid regions of India. *Crop Sci*. **43:** 1680–1689.

Bromley, D. J. 1991 *Environment and Economy: Property Rights and Public Policy*. Basil Blackwell, NY, USA.

Brown, A. H. D. 1990. *Plant Population Genetics, Breeding, and Genetic Resources.* Sinauer Associates Inc., Basingstoke, Hampshire, U.K.

Brown, A.H.D. 2000. The genetic structure of crop landraces and the challenge to conserve them in situ on farms. **In:** *Genes in the Field.* pp. 29–48. Brush, S.B., Eds., IDRC/ International Plant Genetic Resources Institute, Rome, Italy.

Brown, A.H.D., and Brubaker, C. 2000. Genetics and the conservation of Australian wild relatives of crops. *Aust. J. Bot.* **48:** 297–303.

Brown, A. H. D., and Brubaker, C. 2002. Indicators for sustainable management of plant genetic resources: how well are we doing? **In:** *Managing Plant Genetic Diversity.* pp. 249–262. Engles, J. M. M., Rao, V. R., Brown, A. H. D., and Jackson, M. T., Eds., International Plant Genetic Resources Institute, Rome, Italy and CABI Publishing, Wallingford, UK.

Brown, A. H. D., and Hodgkin, T. 2007. Measuring, managing, and maintaining crop genetic diversity on farm. **In:** *Managing Biodiversity in Agricultural Ecosystems.* Jarvis, D. I., Padoch, C., and Cooper, H.D., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Brown, A. H. D., and Rieseberg, L. 2006. Genetic features of populations from stress-prone environments. **In:** *Enhancing the Use Of Crop Genetic Diversity to Manage Abiotic Stress in Agricultural Production Systems.* pp. 2–10. Jarvis, D., Mar, I., and Sears, L., Eds, International Plant Genetic Resources Institute, Rome, Italy.

Brown, G. G., Swift, M. J., Bennack, D. E., Bunning, S., Montáñez, A., and Brussaard, L. 2007. Management of soil biodiversity in agricultural ecosystems. **In:** *Managing Biodiversity in Agricultural Ecosystems*. pp. 224–268. Jarvis, D. I., Padoch, C., and Cooper, H. D., Eds., Bioversity International, Rome, Italy.

Brush, S. B. 2004. *Farmers' Bounty: Locating Crop Diversity in the Contemporary World.* Yale University Press, New Haven, NY, USA.

Brush, S., Kesselli, R., Ortega, R., Cisneros, P., Zimmerer, K., and Quiros, C. 1995. Potato diversity in the Andean center of crop domestication. *Conserv. Biol.* **9**(5): 1189–1198.

Brush, S., and Meng, E. 1998. Farmers' valuation and conservation of crop genetic resources. *Genet. Resour. Crop Ev.* **45:** 139–150.

Brush, S. B., Taylor, J. E., and Bellon, M. R. 1992. Biological diversity and technology adoption in Andean potato agriculture. *J. Dev. Econ.* **39:** 365–387.

Brussaard, L., Caron, P., Campbell, B., Lipper, L., Mainka, S., Rabbinge, R., Babin, D., and Pulleman, M. 2010. Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. *Curr. Opin. Environ. Sustain*. In press doi:10.1016/j.cosust.2010.03.007.

BUCAP 2002. *Field Guide: Farmers' Field School for Rice Plant Genetic Resources Conservation, Development and Use.* SEARICE, Manila, Philippines.

Budenhagen, I. W. 1983. Breeding strategies for stress and disease resistance in developing countries. *Ann. Rev. Phytopathology* **21:** 385–409.

Burgos-May, L. A., Chavez-Servia, J. L., and Ortiz-Cereceres, J. 2004. Variabilidad morfologica de maices criollos de la peninsula de Yucatan, Mexico. **In:** *Manejo de la Diversidad de los Cultivos en los Agroecosistemas Tradicionales*. pp. 58–66. Chavez-Servia, J. L., Tuxill, J. and Jarvis, D. I., Eds., Instituto Internacional de Recursos Fitogeneticos, Cali, Colombia (in Spanish).

Busso, C. S., Devos, K. M., Ross, G., Mortimore, M., Adams, W. M., Ambrose, M. J., Alldrick, S., and Gale, M. D. 2000. Genetic diversity within and among landraces of pearl millet (*Pennisetum glaucum*) under farmer management in West Africa. *Genet. Resour. Crop Ev.* **60:** 1–8.

Butkov, E.A., and Turdieva, M.K. 2009. Sovremennoe rasprostranenie gretskogo orekha v Uzbekistane i raznoobrazie mestnikh sortov. (Current status of walnut distribution in Uzbekistan and diversity of local varieties). **In:** *Materials of the Republican Scientific-Practical Conference on "Conservation and Sustainable Use of Biodiversity of Agricultural Crops and their Wild Relatives."* pp. 28–31. Tashkent, Uzbekistan (In Russian).

Camacho-Villa, C., and Chavez-Servia, J. L. 2004. Diversidad morfologica del maiz criollo de la region centro de Yucatan, Mexico. **In:** *Manejo de la Diversidad de los Cultivos en los Agroecosistemas Tradicionales.* pp. 47–57. Chavez-Servia, J. L., Tuxill, J., and Jarvis, D. I., Eds., Instituto Internacional de Recursos Fitogeneticos, Cali, Colombia (in Spanish).

Campbell, B., Hagmann, J., Sayer, J., Stroud, A., Thomas, R., and Wollenberg, E. 2006. What kind of research and development is needed for natural resource management? *Water Int.* **31:** 343–360.

Canh, N. T., On, T. V., Trung, N. V., Tiep, C. A. ,and Lam H. V. 2003. Preliminary study of genetic diversity in rice landraces in Ban Khoang Commune, Sa Pa District. **In:** *On-Farm Management of Agricultural Biodiversity in Vietnam. Proceedings of a symposium, December 6–12, 2001, Hanoi, Vietnam.* Tuan, H. D., Hue, N. N., Sthapit, B. R. and Jarvis, D. I., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Cazarez-Sanchez, E. 2004. *Diversidad Genetica y su Relacion con la Tecnologia de Alimentos Tradicionales*. MS thesis, Colegio de Postgraduados, Montecillos, Texcoco, Mexico (in Spanish).

Cazarez-Sanchez, E., and Duch-Gary, J. 2004. La diversidad genetica de variedades locales de maiz, frijo, calabaza y chile, y su relacion con caracteriticas culinarias. **In:** *Manejo de la Diversidad de los Cultivos en los Agroecosistemas Tradicionales.* pp. 250–255. Chavez-Servia, J. L., Tuxill, J., and Jarvis, D. I., Eds., Instituto Internacional de Recursos Fitogeneticos, Cali, Colombia (in Spanish).

Cázares-Sánchez, E., Ramírez-Vallejo, P., Castillo-González1, F., Soto-Hernández, R. M., Rodríguez-González, M. T., and Chávez-Servia, J. L. 2005. Capsaicinoids and preference of use in different morphotypes of chili peppers (*Capsicum annuum* L.) of East-central Yucatan. *Agrociencia* **39:** 627–638.

Carpenter, S. R., Bennett, E. M., and Peterson, G. D. 2006. Scenarios for ecosystem services: an overview. *Ecol. Soc.* **11**(1): 29. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art29/

Caviglia, J. L., and Kahn, J. R. 2001. Diffusion of sustainable agriculture in the Brazilian tropical rain forest: a discrete choice analysis. *Econ. Dev. Cult. Change* **49:** 311–333.

Ceccarelli, S., and Gando, S. 2007. Decentralized-participatory plant breeding: an example of demand driven research. *Euphytica* **155:** 349–360.

Ceccarelli, S., Guimaraes, E. P., and Weltzien, E. 2009. *Plant Breeding and Farmer Participation*. United National Food and Agricultural Organization (FAO), Rome, Italy.

Celis-Velázquez, R., Peña-Valdivia, C. B., Trejo-López, C., Aguirre-Rivera, J. R., Cordova-Téllez, L., and Carballo-Carballo, A. 2008. Consumption of common bean seed reserves for emergence and development of seedlings under different sowing depths. *Agron. Mesoam.* **19**(2): 167–177.

Ceroni, M., Liu, S., and Constanza, R. 2007. Ecological and economic roles of biodiversity in agroecosystems. **In:** *Managing Biodiversity in Agricultural Ecosystems.* pp. 446–472. Jarvis, D. I., Padoch, C., and Cooper H. D., Eds., Columbia University Press, NY, USA.

Chable, V., 2005. Conserving and developing crop biodiversity. **In:** *Biodiversity and Local Ecological Knowledge in France*. pp. 46–49, Bérard, L., Cegarra, M., Djama M., Louafi S., Marchenay P., Roussel B., Verdeaux F., Eds. Publisher Cemagref, Cirad, Ifremer, INR; IDDRI, IFB, Montpellier, France.

Chakauya, E., Tongoona, P., Matibiri, E. A., and Grum, M. 2006. Genetic diversity assessment of sorghum landraces in Zimbabwe using microsatellites and indigenous local names. *Int. J. Bot.* **2**(1): 29–35.

Chaudhary, P., Gauchan, D., Rana, R. B., Sthapit, B. R., and Jarvis, D. I. 2004. Potential loss of rice landraces from a Terai community in Nepal: A case study from Kachorwa, Bara. *Plant Genet. Resour. Newsl.* **137:**14–21.

Chavez-Servia, J. L., Burgos-May, L., Canul-Ku, J., Camacho, T. C., Vidal-Cob, J., and Arias-Reyes, L. M. 2000. Analisis de la diversidad en un proyecto de conservacion in situ en Mexico [Diversity analysis of an in situ conservation project in Mexico]. **In:** *Proceedings of the XII Scientific Seminar, November 14–17, 2000*. Havana, Cuba (in Spanish).

Chiffoleau, Y., and Desclaux, D. 2006. Participatory plant breeding: the best way to breed for sustainable agriculture? *Int. J. Agric. Sustain.* **4**(2): 119–130.

CIP-UPWARDS. 2003. *Conservation and Sustainable Use of Agricultural Biodiversity: A Source Book Vol I: Understanding Agricultural Biodiversity.* International Potato Centre (CIP) and User's Perspectives with Agricultural Research and Development (UPWARD), Los Banos, Philippines.

Clegg, M. T. 1997. Plant genetic diversity and the struggle to measure selection. *Heredity* **88:** 1–7.

Collado-Panduro, L., Chavez-Servia, J. L., Riesco, A., and Soto, R. 2005. Community systems of seed supply and storage in the central Amazon of Peru. **In:** *Seed Systems and Crop Genetic Diversity On-Farm. Proceedings of a Workshop, September 16–20, 2003*. pp. 103–108. Jarvis, D. I., Sevilla-Panizo, R., Chavez-Servia J. L., and Hodgkin, T., Eds., Pucallpa, Peru. International Plant Genetic Resources Institute, Rome, Italy.

Convention on Biological Diversity, 2010. Access to Genetic Resources and Benefit-sharing Database on Capacity Building Projects. http://www.cbd.int/abs/projects.shtml

Coomes, O. T. 2001. Crop diversity in indigenous farming systems of Amazonia: the role and dynamics of agricultural planting stock transfers among traditional 112 seed systems and crop genetic diversity farmers. **In:** *Abstracts. International Symposium on Managing Biodiversity in Agricultural Ecosystems,* 27, November 8–10, 2001, Montreal, Canada.

Cooper, D. 1993. *Plant Genetic Diversity and Small Farmers: Issues and Options for IFAD.* Staff Working Paper 13. International Fund for Agricultural Development (IFAD), Rome, Italy.

Correa, C., 2000. *Options for the Implementation of Farmers' Rights at the National Level.* South Centre: Working Paper 8, December 2000.

Correa, C. In press. Sui generis intellectual property protection for farmers' varieties. **In:** *Farmers' Varieties and Farmers' Rights: Addressing Challenges in Taxonomy and Law*. Halewood, M., Ed. Earthscan. London, UK.

Cramb, R. A. and Culasero, Z. 2003. Landcare and livelihoods: the promomotion and adoption of conservation farming systems in The Philippine uplands. *Int. J. Sustain.* **1:** 141–154.

Cromwell, E., and Almekinders, C. 2000. The impact of seed-supply interventions on the use of crop genetic diversity. **In:** *Encouraging Diversity - The Conservation and Development of Plant Genetic Resources.* pp. 223–227. Almekinders, C. and de Boef, W., Eds., Intermediate Technology Publications, London, UK.

Cromwell, E., Wiggens, S., and Wentzel, S. 1993. *Sowing Beyond the State: NGOs and Seed Supply in Developing Countries.* Overseas Development Institute, London UK.

CRS, ICRISAT, and ODI. 2002. *Seed Vouchers and Fairs: A Manual for Seed-Based Agricultural Recovery After Disaster in Africa.* Nairobi: Catholic Relief Services. Available on-line at http://www.foodaid.org/Tzehay/crs8199.pdf.

Dalton, T. J., Anderson, C. L., Lipper, L., and Keleman, A. 2010. Markets and access to crop genetic resources. **In:** *Seed Trade in Rural Markets: Implications for Crop Diversity and Agricultural Development*. pp: 2–30. Lipper, L., Anderson, C. L. and Dalton, T. J., Eds., United National Food and Agricultural Organization (FAO), Rome, Italy.

Danial, D., Parlevliet, J., Almekinders, C., Thiele, G., and Niks, R. 2007. Farmers' participation and breeding for durable disease resistance in the Andean region. *Euphytica* **153**(3): 385–396.

Dawson J. C., Murphy, K. M., and Jones, S. S. 2008. Decentralized selection and participatory approaches in plant breeding for low-input systems. *Euphytica* **160:** 143–154.

De, N. N. 2000. Crop improvement at community level in Vietnam. **In:** *Participatory approaches to the conservation and use of plant genetic resources.* pp. 103–110. Friis-Hansen, E., and Sthapit, B., Eds., International Plant Genetic Resources Institute, Rome Italy.

De Boef, W. S., Dempewolf, H., Byakwell, J. M. and Engles, J. M. M. 2010. Integrating genetic resource conservation and sustainable development into strategies to increase the robustness of seed systems. *J. Sustain. Agric.* **34** :1–28.

Demissie, A., and Bjørnstad, Å, 2004. Phenotypic diversity of Ethiopian barleys in relation to geographical regions, altitudinal range, and agro-ecological zones: as an aid to germplasm collection and conservation strategy. *Hereditas* **124:** 17–29.

Deu, M., Sagnard, F., Chantereau, J., Calatayud, C., Herault, D., Mariac, C., Pham, J. L., Vigouroux, Y., Kapran, I., Traore, P. S., Mamadou, A., Gerard, B., Ndjeunga, J., and Bezancon, G. 2008. Niger-wide assessment of in situ sorghum genetic diversity with microsatellite markers. *Theor. Appl. Genet.* **116**(7): 903–913.

Devaux, A., Bernet, T., Lopez, G., and Velasco, C. 2006. *Papa Andina: Innoavacion Para el Desarrollo en los Andes – Logros y Experiencia de la Seguand Fase: 2002-2006*. International Ptoato Center (CIP), Lima, Peru (in Spanish).

Devkota, K. P., Tripathi, M. P., Joshi, K. D., Shrestha, P. K., and Witcombe, J. R. 2008. Community based seed production groups in Chitwan, Nepal. **In:** *Farmers, Seeds and Varieties. Supporting Informal Seed Supply in Ethiopia.* pp. 263–270. Thijssen, M. H., Bishaw, Z., Beshir, A. and de Boef, W. S., Eds., Wageningen International, The Netherlands.

Dewan, S., Tiwari, R. K., Pageni, S., Rijal, D., Baral, K. P., Chaudhary, P., Rana, R. B., Subedi, A., and Sthapit, B. 2006. Rural poetry journey: an effective approach to sensitize farming community. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K. and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Di Falco, S., and Chavas, J. P. 2007. On the role of crop biodiversity in the management of environmental risk. **In:** *Biodiversity Economics.* pp. 581–593. Kontoleon, A., Pascual, U. and Swanson, T. M., Eds., Cambridge University Press, Cambridge, UK.

Di Falco, S., and Perrings, C. 2005. Crop biodiversity, risk management and the implications of agricultural assistance. *Ecol. Econ.* **55:** 459–466.

Djumabaeva, S. A. 2009. Orekh gretskiy Yujnogo Kyrgyzstana. (Walnut in the South Kyrgyzstan). *Vestnik of Kyrgyz Technical University:* 1. Bishkek, Kyrgyzstan (in Russian).

Djavakyants, Yu. M. 2009; Znachenie sokhraneniya i ispolzovaniya mestnikh sortov i dikorastushikh form vinograda v proizvodstve i selektsii. (Role of conservation and use of local varieties and wild species of grapevine in production and selection). **In:** *Materials of the Republican Scientific-Practical Conference On "Conservation and Sustainable Use of Biodiversity of Agricultural Crops and Their Wild Relatives.*" pp. 31–35. Tashkent, Uzbekistan. (in Russian).

Djavakyants, Yu. M. 2010. Tekhnologiya virashivaniya i razmnojenie mestnikh sortov i form yabloni i grushi. (Cultivation and propagation technologies of local varieties and forms of apple and pear.). *Interpress.*Tashkent, Uzbekistan (in Russian).

Dominguez, C. E., and Jones, R. B. 2005. The dynamics of local seed systems in Mozambique, and the roles played by women. **In:** *Seed Systems and Crop Genetic Diversity On-Farm, Proceedings of a workshop, September 16–20, 2003.* pp. 141–148. Jarvis, D. I., Sevilla- Panizo, R., Chavez-Servia, J. L., and Hodgkin, T., Eds., Pucallpa, Peru. International Plant Genetic Resources Institute, Rome, Italy.

Dossou, B., Balma, D., and Sawadogo, M. 2004. Le role et la participation des femmes dans le processus de la conservation in situ de la biodiversite biologique agricole au Burkina Faso. **In:** *La Gestion de la Diversité des Plantes Agricoles dans les Agro-Ecosystemes.* pp. 38–44.Compte-rendu des travaux d'un atelier abrité par CNRST, Ouagadougou, Burkina Faso, 27-28 décembre 2002. Balma, D., Dossou, B., Sawadogo, M., Zangre, R. G., Ouédraogo, J. T., and Jarvis, D. I., Eds., International Plant Genetic Resources Institute, Rome, Italy (in French).

Duc, G., Bao, S., Baum, M., Redden, B., Sadiki, M., Suso, M.J., Vishniakova, M., and Zong, X. 2010. Diversity maintenance and use of *Vicia faba* L. genetic resources. *Field Crop Res.* **115:** 270–278.

Dudnik, N. S., Thormann, I., and Hodgkin, T. 2001. The extent of use of plant genetic resources in research- a literature survey. *Crop Sci.* **41:** 6–10.

Dyer, G. A., and Taylor, J. E. 2008. A crop population perspective on maize seed systems in Mexico. *Proc. Nat. Acad. Sci.* **105**(2): 470–475.

Edmeades, S. 2006. *A Hedonic Approach to Estimating The Supply of Variety Attributes of a Subsistence Crop.* Environmental and Production Technology Discussion paper No. 148. International Food Policy Research Institute, Washington, DC, USA.

Edmeades, S., and Smale, M. 2009. Market participation and crop biodiversity in developing economy: bananas in Uganda. **In:** *Agrobiodiversity, Conservation and Economic Development.* pp. 353–367. Kontoleon, A., Pascual, U., and Smale, M., Eds., Routledge Oxon, UK.

Edmeades, S., Smale, M., and Karamura, D. 2006. Demand for cultivar attributes and the biodiversity of bananas on farm in Uganda. **In:** *Valuing Crop Biodiversity: On-farm Genetic Resources and Economic Change.* pp. 97–118. Smale, M., Eds., CABI Publishing, Wallingford, UK.

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B., and Norberg, J. 2003. Response diversity, ecosystem change, and resilience. *Front. Ecol. Environ.* **1**(9): 488–494.

Engels, J. M. M., Polreich, S., and Dullo, M. E. 2008. Role of community gene/seedbanks in the conservation and use of crop genetic resources in Ethiopia. **In:** *Farmer's Varieties and Seeds. Supporting Informal Seed Supply in Ethiopia.* pp. 149–159. Thijssen, M. H., Bishaw, Z., Beshir, A., and de Boef, W. S., Eds., Wageningen, Wageningen International.

Eyzaguirre, P., and Dennis, E. M. 2007. The impact of collective action and property rights on plant genetic resources. *World Dev.* **35**(9): 1489–1498.

Eyzaguirre, P., and Linares, O. F. 2004. *Home Gardens and Agrobiodiversity.* Smithsonian Books, Washington, DC, USA.

Evenson, R. E., Gollin, D., and Santaniello, V. (Eds.) 1998. *Agricultural Values of Plant Genetic Resources*. CABI Publishing, Wallingford, UK.

Fan, S., Brzeska, J., and Shields, G. 2007. *Investment Priorities for Economic Growth and Poverty Reduction. 2020 Focus Brief on the World's Poor and Hungry People.* IFPRI, Washington, DC, USA.

FAO. 1993. *Quality Declared Seed System*. FAO Plant Production and Production Paper No. 117. United National Food and Agricultural Organization (FAO). Rome, Italy.

FAO. 1998. *Developing Seed Security Strategies and Programmes for Food Security in Developing Countries.* Proceedings of the International Workshop on Seed Security for Food Security, 30 November to 1 December 1997, Florence, Italy. Food and Agriculture Organization of the United Nations, Seed and Plant Genetic Resources Service, Rome, Italy.

FAO. 2005. *Building on Gender, Agrobiodiversity and Local Knowledge, A Training Manual.* United National Food and Agricultural Organization (FAO), Rome, Italy.

FAO. 2006a. *Community Diversity Seed Fairs in Tanzania: Guidelines for Seed Fairs.* FAO-LinKS Project. Report No. 51. United National Food and Agricultural Organization (FAO), Rome, Italy.

FAO. 2006b. *Quality Declared Seed System*. FAO Plant Production and Protection Paper No. 185. United National Food and Agricultural Organization (FAO). Rome, Italy.

FAO. 2007. *State of Food and Agriculture Report: Paying Farmers for Environmental Services*, http://www.fao.org/docrep/010/a1200e/a1200e00.htm. United National Food and Agricultural Organization (FAO), Rome, Italy.

FAO. 2010. *Second Report on the World's Plant Genetic Resources for Food and Agriculture.* [in press]. Electronic version ftp://ftp.fao.org/docrep/fao/meeting/017/ak528e.pdf. United National Food and Agricultural Organization (FAO), Rome, Italy.

Farm Seed Opportunities, 2009. http://www.farmseed.net/home/

Farmers' Rights, 2010. http://www.farmersrights.org/about/fr_contents.html

Feyissa, R. 2000. Community seed banks and seed exchange in Ethiopia: a farmer-led approach. **In:** *Participatory Approaches to the Conservation and Use of Plant Genetic Resources.* pp. 142–148. Friis-Hansen, E., and Sthapit, B. R., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Feyissa, R. 2006. *Farmers' Rights in Ethiopia – A Case Study*. FNI report7/2006, FNI, Lysaker, Norway.

Finckh, M. R. 2008. Integration of breeding and technology into diversification strategies for disease control in modern agriculture. *Eur. J. Plant Pathol.* **121:** 399–409.

Finckh, M. R. 2003. Ecological benefits of diversification. **In:** *Rice Science: Innovations and Impact for Livelihood.* pp. 549–564. Proceedings of the International Rice Research Conference, September 16–19, 2002. Mew, T. W., Brar, D. S., Peng, S., Dawe, D., and Hardy, B., Eds., Beijing: International Rice Research Institute, Chinese Academy of Engineering and Chinese Academy of Agricultural Sciences.

Finckh, M. R., Gacek, E. S., Goyeau, H. *et al*. 2000. Cereal variety and species mixtures in practice, with emphasis on disease resistance. *Agronomie* **20:** 813–837.

Finckh, M. R., and Wolfe, M. S. 2006. Diversification strategies. **In:** *The Epidemiology of Plant Disease*. pp. 269–308. Cooke, B. M. *et al*. Eds., Springer, NY, USA.

Folke, C. 2006. Resilience: the emergence of a perspective for social–ecological systems analyses. *Global Environ. Change* **16**(3): 253–267.

Folke, C., Carpenter, S. R., Elmqvist, T. *et al*. 2002. Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio* **31:** 437–440.

Fowler, C., and Hodgkin, T. 2004. Plant genetic resources for food and agriculture: assessing global availability. *Ann. Rev. Environ. Res.* **29:** 143–179.

Frankel, O. H., Brown, A. H. D., and Burdon, J. J. 1995. *The Conservation of Plant Biodiversity*. Cambridge University Press, Cambridge, UK.

Frankel, O., and Soulé, M. 1981. *Conservation and Evolution*. New York, USA.

Friis-Hansen, E., Lilja, N., and Dixon, J. 2008. Impact assessment of farmer institutional development and agricultural change: Soroti district, Uganda. *Dev. Pract.* **18**(4/5): 506–523.

Friis-Hansen, E., and Sthapit, B. R. 2000. *Participatory Approaches to the Conservation and Use of Plant Genetic Resources.* International Plant Genetic Resources Institute Rome, Italy.

Fu YongNeng, Guo HuiJun, Chen AiGuo and Cui JinYun, 2006. Household differentiation and on-farm conservation of biodiversity by indigenous households in Xishuangbanna, China. *Biodivers. Conserv.* **15**(8): 2687–2703.

Gagne, G., and Ratanasatien, C. In press. Commentary on Thailand's plant variety protection act. **In:** *Farmers' Varieties and Farmers' Rights: Addressing Challenges in Taxonomy and Law*. Halewood, M., Ed., Earthscan. London, UK.

Gaifani, A. 1992. Developing local seed production in Mozambique. **In:** *Growing Diversity.* pp. 97–105. Cooper, D., Vellvé, R. and Hobbelink, H., Eds., Intermediate Technology Publications, London, UK.

Garcia, C., Marie-Vivien, D., Kushalappa, C. G., Chengappa, P. G., and Nanaya, K. M. 2007. Geographical indications and biodiversity in the Western Ghats, India. Can labeling benefit producers and the environment in a mountain agroforestry landscape? *Mount. Res. Dev.* **27:** 206–210.

Garforth, C., Holt, G., Subedi, A., Regmi, B., McKemey, K., Gauchan, D., Tripathi, B., Ellis-Jones, J., Stocking, M., Helleman, H., and White, R. 2005. Linking field-level findings to policy and decision-making in Nepal. **In:** *Renewable Natural Resources Management for Mountain Communities.* pp. 239–246. ICIMOD, Kathmandu, Nepal.

Garrett, K. A., and Mundt, C. C. 1999. Epidemiology in mixed host populations. *Phytopathology* **89:** 984–990.

Gauchan, D., and Smale, M. 2003. Choosing the "right tools" to assess the economic costs and benefits of growing landraces: an illustrative example from Bara District, Central Terai, Nepal. *Plant Genet. Resour. Newsl.* **134:** 41–44.

Gauchan, D., and Smale, M. 2007. Comparing the choices of farmers and breeders: the value of rice land races in Nepal. **In:** *Managing Biodiversity in Agricultural Ecosystems*. pp. 407–425. Jarvis, D. I., Padoch, C., and Cooper, H. D., Eds., Columbia University Press, NY, USA.

Gauchan, D., Smale, M., and Chaudhary, P. 2005. Market-based incentives for conserving diversity on farms: the case of rice landraces in Central Tarai, Nepal. *Genet. Resour. Crop Ev.* **52**(3): 293–303.

Gauchan, D., Smale, M., Maxted, N., and Cole, M. 2006. Managing rice biodiversity on-farms: the choices of farmers and breeders in Nepal. **In:** *Valuing Crop Biodiversity: On-farm Genetic Resources and Economic Change.* pp. 162–177. Smale, M. Eds., CABI Publishing, Wallingford, UK.

Gautam, R., Sthapit, B., Subedi, A., Poudal, D., Shrestha, P., and Eyzaguirre, P. 2008. Home gardens management of key species in Nepal: A way to maximise the use of useful diversity for the well being of poor farmers. *Plant Genet. Resour. Charact. Utiliz.* **7**(2): 142–153.

Gautam, R., Suwal, R., and Sthapit, B. R. 2009. Securing family nutrition through promotion of home gardens: underutilized production systems in Nepal. *Acta Hortic.* **806:** 99–106.

Gepts, P. 1990. Biochemical evidence bearing on the domestication of Phaseolus (*Fabaceae*) beans. *Econ. Bot.* **44:** 28–38.

Gepts, P. 2006. Plant genetic resources conservation and utilization: the accomplishments and future of a societal insurance policy. *Crop Sci.* **46:** 2278–2292.

Gibson, R. W. 2009. A review of perceptual distinctiveness in landraces including an analysis of how its roles have been overlooked in plant breeding for low-input farming systems. *Econ. Bot.***63**(3): 242–255.

Gildemacher, P.R., Demo, P., Barker, I., Kaguongo, W., Woldegiorgis, G., Wagoire, W. W., Wakahiu, M., Leeuwis, C., and Struikl, P.C. 2009. A description of seed potato systems in Kenya, Uganda and Ethiopia. *Am. J. Pot. Res.* **86:** 373–382.

Gine, X., and Yang, D. 2009. Insurance, credit, and technology adoption: field experimental evidence from Malawi. *J. Dev. Econ.* **89:** 1–11.

Giuliani, A. 2007. *Developing Markets for Agrobiodiversity*. *Securing Livelihoods in Dryland Areas*. Earthscan Research Editions, London, UK.

Gold, C. S., Kiggundu, A., Abera, A. M. K., and Karamura, D. 2002. Diversity, distribution and farmer preference of *Musa* cultivars in Uganda. *Exp. Agric.* **38**(1): 39–50.

Gollin, D., and Evenson, R. E. 1998. **In:** *Valuing Genetic Diversity: Crop Plants and Agroecosystems. Biodiversity in Agroecosystems.* Gollin, D. and Smale, M., Eds., 1999, CRC Press, London, UK.

Gollin, D. and Smale, M. 1999. *Valuing Genetic Diversity: Crop Plants and Agroecosystems. Biodiversity in Agroecosystems.* CRC Press, London, UK.

Grain, 2005. Africa's seed laws: red carpet for the corporations. *Seedling*, July. Grain Publications, Barcelona, Spain.

Granovetter, M. 1973. The strength of weak ties. *Am. J. Sociol.* **78:** 1360–1380.

Granquist, B. 2009. *Is Quality Declared Seed Production an Effective and Sustainable Way to Address Seed and Food Security in Africa?* http://knowledge.cta.int/en/Dossiers/Demanding-Innovation/Demanding-Innovation/Articles/Is-Quality-Declared-Seed-Production-an effective-and-sustainable-way-to-address-Seed-and-Food-Security-in-Africa (*accessed 21 May 2010*)

Gruere, G. P., Nagarajan, L., and King, E. 2007. *Collective Action and Marketing of Underutilized Plant Species: Case of Minor Millets in Kolli Hills, Tamil Nadu, India.* CAPRi Working Paper 68. International Food Policy Research Institute, Washington, USA.

Grum, M., Guerette, V., Kone, B., Sidibe, A., Kouressy, M., Huvio, T., Mafa, A., Mujaju C., Bretaudeau, A., Vaxmann, M., Ouatara, M., Traore, I., Butaumocho, B., Zinanga, F., Mamadou, O. 2003. Strategies for in situ conservation of crop genetic resources in dryland areas of Africa. **In:** *Conserving Biodiversity in Arid Regions.* pp. 55–62. Lemons, E., Victor, R. and Schaffer, D. Eds., Kulwer, Academic Publishers, The Netherlands.

Grum, M., Gyasi, E. A., Osei, C., and Kranjac-Berisavljevie, G. 2003. *Evaluation of Best Practices for Landrace Conservation: Farmer Evaluation*. Paper presented at Sub-Saharan Africa Meeting, International Plant Genetic Resources Institute, Nairobi, Kenya.

Guerette, V., Sibdibe, A., Ouatara, M., and Grum M. In prep. *Measuring the Impacts of Seed Diversity Fairs as a Strategy of Support on Farm Conservation of Plant Genetic Resource.* International Plant Genetic Resources Institute and IER/USC-Canada. (unpublished).

Gupta, S. R., Bajracharya, J., Upadhyay, M. P., Baniya, B. K., Tiwari, P. R., Shakya, D. M., and Sthapit, B. R. 2003. Agromophological characterization of barley (*Horedeum vulgare* L.) landraces of Jumla, Nepal. **In:** *On-farm Management of Agricultural Biodiversity in Nepal. Proceedings of a National Workshop, 24-26. April 2001, Lumle, Nepal.* pp: 37–41. Sthapit, B. R., Upadhyay, M. P., Baniya, B. K., Subedi, A., and Joshi, B. K., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute, Kathmandu, Nepal.

Guzman, F. A., Ayala, H., Azurdia, C., Duque, M. C., and Vicente, M. C. 2005. AFLP assessment of genetic diversity of *Capsicum* genetic resources in Guatemala: home gardens as an option for conservation. *Crop Sci.* **45**(1): 363–370.

Gyawali, S., Gautam, R., Upadhyay, M. P., and Gauchan, D. 2006. Travelling seminar: influencing policy. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R, Shrestha, P. K., and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute, IDRC, Kathmandu, Nepal.

Gyawali, S., Sthapit, B., Bhandari, B., Gauchan, D., Joshi, B. K., Tripathi, M., Shrestha, P. K., Joshi, K. D., and Mudwari, A. 2006. Participatory landrace enhancement: an economic incentive to support on-farm management. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R, Shrestha, P. K., and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Gyawali, S., Sthapit, B., Joshi, B. K., Mudwari, A., and Bajracharya, J. 2006. Participatory plant breeding (PPB): a strategy of enhancing and maintaining local crop diversity. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K., and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute, IDRC, Kathmandu, Nepal.

Gyawali, S., Sthapit, B. R., Bhandari, B., Bajracharya, J., Shrestha, P. K., Upadhyay, M. P., and Jarvis D. I. 2009. Participatory crop improvement and formal release of Jethobudho rice landrace in Nepal. *Euphytica*. DOI. 1007/S10681–010–0213–0.

Gyawali, S., Sunwar, S., Subedi, M., Tripathi, M., Joshi, K. D., and Witcombe, J.R. 2007. Collaborative breeding with farmers can be effective. *Field Crop Res.* **101:** 88–95.

Hajjar, R., Jarvis, D. I., and Gemmill, B. 2008. The utility of crop genetic diversity in maintaining ecosystem services. *Agric. Ecosyst. Environ.* **123:** 261–270.

Halewood, M., Deupmann, P., Sthapit, B. R., Vernooy, R. and Ceccarelli, S. 2007. *Participatory plant breeding to promote farmers' rights*. Opinion paper Bioversity International, ICARDA, IDRC and GRPI, Rome, Italy.

Hamrick, J. L., and Godt, M. J. W. 1997. Allozyme diversity in cultivated crops. *Crop Sci.* **37:**26–30.

Hardon, J., and de Boef, W. 1993. Linking farmers and breeders in local crop development.**In:** *Cultivating Knowledge: Genetic Diversity, Farmer Experimentation and Crop Research.* pp. 64–71. de Boef, W., Amanor, K., Wellard, K. and Bebbington, A., Eds., Intermediate Technology Publications. London, UK.

Harlan, J.R. 1975. Our vanishing genetic resources. *Science* **188:** 618–621.

Heerwaarden, van, J., van Eeuwijk, F. A., and Ross-Ibarra, J. 2010. Genetic diversity in a crop metapopulation. *Heredity* **104:** 28–39.

Hodgkin, T., Rana, R., Tuxill, J., Didier, B., Subedi, A., Mar, I., Karamura, D., Valdivia, R., Collado, L., Latournerie, L., Sadiki, M., Sawadogo, M., Brown A. H. D., and Jarvis, D. 2007. Seed systems and crop genetic diversity in agroecosystems. **In:** *Managing Biodiversity in Agricultural Ecosystems*. pp. 77–116. Jarvis, D. I., Padoch, C., and Cooper, D., Eds., Columbia University Press, NY, USA.

Howard, P. L. 2003. Women and the plant world: an exploration. **In:** *Women and Plants, Gender Relations in Biodiversity Management and Conservation.* pp. 1–31. Howard, P., Eds., Zed Books, NY, USA.

Hue, N. and In situ Project staff. 2006. On-farm conservation of rice genetic diversity under salinity stress: case study in a lowland agrosystem of Vietnam. **In:** *Enhancing the Use of Crop Genetic Diversity to Manage Abiotic Stress* *in Agricultural Production Systems.* Proceedings of a workshop, 23–27 May 2005, Budapest, Hungary. pp 49–54. Jarvis, D. I., Mar, L., and Sears, L., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Hue, N., Trinh, L., Ha, N., Sthapit, B., and Jarvis, D. 2003. Taro cultivar diversity in three ecosites of North Vietnam. **In:** *On-Farm Management of Agricultural Biodiversity in Vietnam*. Proceedings of a symposium, December 6–12, 2001, Hanoi, Vietnam. Tuan, H. D., Hue, N. N., Sthapit, B. R. and Jarvis D. I., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Huvio, T., and Sidibe, A. 2003. Strengthening farmers' capacities for plant genetic resources conservation in Mali. *Plant Genet. Res.* **1:** 31–41.

IAASTD., 2009. Agriculture at a crossroads. **In:** *International Assessment of Agricultural Knowledge, Science and Technology for Development.* McIntyre, B. D., Herren, H. R., Wakhungu J. and Watson R. T., Eds, Island Press, Washington, DC, USA.

Iriarte, V., Terrazas, F., Aguirre, G., and Thiele, G. 2000. Local seed system and Proinpa's genebank: working to improve seed quality of traditional Andean potatoes in Bolivia and Peru. **In:** *Participatory Approaches to the Conservation and Use of Plant Genetic Resources.* pp. 154–161. Friis-Hansen, E. and Sthapit, B., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Irungu, C., Mburu, J., Maundu, P., Grum, M., Hoeschle-Zeledon, I., Chadha, M. L., Kuo, G., and Gowda, C. L. L. 2007. Marketing of African leafy vegetables in Nairobi and its implications for on-farm conservation of biodiversity. *Acta Hortic.* **752:** 197–201.

Jackson, L. E., Burger, M., and Cavagnaro, T. R. 2008. Roots, nitrogen, transformations, and ecosystem services. *Ann. Rev. Plant Biol.* **59:** 341–363.

Jackson, L. E., Pascual, U., and Hodgkin, T. 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agric. Ecosyst. Environ.* **121:** 196–210.

Jackson, L., van Noordwijk, M., Bengtsson, J., Foster, W., Lipper, L., Pulleman, M., Said, M., Snaddon, J. and Vodouhe, R. 2010. Biodiversity and agricultural sustainability: from assessment to adaptive manage. *Curr. Opin. Environ. Sustain.* On line version, doi:10.1016/j.cosust.2010.02.007.

Jaffe, W. ,and Jeroen Van Wijk, 1995. *The Impact of Plant Breeders Rights in Developing Countries: Debate and Experience in Argentina, Chile, Colombia, Mexico and Uruguay.* DGIS. The Hague, Netherlands.

Janssen, W., Luna, C. A., and Duque, M. C. 1992. Small farmer behaviour towards bean seed: evidence from Colombia. *J. App. Seed Prod.* **10:**43–51.

Jarvis, D. I., Brown, A. H. D., Cuong, P. H., Collado-Panduro, L., Latourniere-Moreno, L., Gyawali, S., Tanto, T., Sawadogo, M., Mar, I., Sadiki, M., et. al. 2008. A global perspective of the richness and evenness of traditional crop variety diversity maintained by farming communities. *Proc. Nat. Acad. Sci.* **108:** 5326–5331.

Jarvis, D. I., Brown, A. D. H., Imbruce, V., Ochoa, J., Sadiki, M., Karamura, E., Trutmann, P., and Finckh, M. R. 2007a. Managing crop disease in traditional agroecosystems: the benefits and hazards of genetic diversity. **In:** *Managing Biodiversity in Agricultural Ecosystems.* pp. 292–319. Jarvis, D. I., Padoch, C, and Cooper, D., Eds., Columbia University Press, NY, USA.

Jarvis, D. I., and Campilan, D.M. 2006. *Crop Genetic Diversity to Reduce Pests and Diseases On-Farm: Participatory Diagnosis Guidelines. Version I.* Bioversity International Technical bulletin No. 12. Bioversity International, Rome, Italy.

Jarvis, D. I., and Hodgkin, T. 2008. The maintenance of crop genetic diversity on farm: supporting the convention on biological diversity's programme of work on agricultural biodiversity. *Bioversity* **9:** 23–38.

Jarvis, D.I., Myers, M., Klemick, H., Guarino, L., Smale, M., Brown, A.H.D., Sadiki, M., Sthapit, B., and Hodgkin, T. 2000. *A Training Guide for in Situ Conservation On-Farm: Version 1.* International Plant Genetic Resources Institute, Rome, Italy.

Jarvis, D., and Ngung'u-Skilton, J. 2000. IPGRI in situ project: research and institutions supporting local management of agrobiodiveristy. **In:** *Encouraging Diversity. The Conservation and Development of Plant Genetic Resources.* pp. 134–141. Almekinders, C. and de Boef, W., Eds., Intermediate Technology Publications, London, UK.

Jarvis, D. I., Padoch, C., and Cooper, H. D. 2007b. *Managing Biodiversity in Agricultural Ecosystems.* Columbia University Press, NY. USA.

Jarvis, D. I., Zoes, V., Nares, D., and Hodgkin, T. 2004. On-farm management of crop genetic diversity and the convention on biological diversity's programme of work on agricultural biodiversity. *Plant Genet. Resour. Newsl.* **138:** 5–17.

Johns, T., and Sthapit, B. R. 2004. Biocultural diversity in the sustainability of developing country food systems. *Food Nutr. Bull.* **25:** 143–155.

Joshi, K. D., Biggs, S., Gauchan, D., Devkota, K. P., Devkota, C. K., Shrestha, P. K., Sthapit, B. R., Harris, D., Richards, J. I., Silverside, P., Ward, A. F., and Wircombe, J. R. 2005. Institutional innovations in the Nepal rice improvement system. *Aspects App. Biol.* **75:** 93–97.

Joshi, K. D., and Sthapit, B. R. 1990. *Informal Research and Development (IRD): A New Approach to Research and Extension. LARC Discussion Paper 1990/4.* Lumle Agricultural Research Centre, Pokhara, Nepal.

Joshi, K. D., Sthapit, B. R., Gurung, R. B., Gurung, M. B., and Witcombe, J. R. 1997. Machhapuchhre 3 (MP-3), the first rice variety developed through a participatory plant breeding approach released for mid to high altitudes of Nepal. *Int. Rice Res. Notes* **22**(2): pp 12.

Joshi, K. D., Sthapit, B. R., Subedi, M., and Witcombe, J. R. 2002. Participatory plant breeding in rice in Nepal. **In:** *Farmers, Scientists and Plant Breeding Integrating Knowledge and Practice.* pp. 239–268. Cleveland D. A., and Soleri D., Eds., CABI Publishing, Wallingford, UK.

Joshi, K. D., Sthapit, B. R., and Witcombe, J. R. 2001. How narrowly are the products of decentralized breeding? The spread of rice varieties from a participatory plant breeding programme in Nepal. *Euphytica* **122:** 589–597.

Jost, L. 2010. The relation between evenness and diversity. *Diversity* **2:** 207–232.

Kabambe, V. H., Mhango, W. G., Msiska, M., Msuku, W. A. B., Nyirenda G. K. C., and Masangano, C. 2008. Facilitating food crop production in Lungwena, Mangochi District in Malawi: lessons from a farmer-based pass-on seed support model. *Afr. J. Agric. Res.***3**(6): 440–447.

Kapila, S., and Mead, D. C., 2002. *Building Businesses with Small Producers: Successful Business Development Services in Africa, Asia, and Latin America.* ITDG Publishing, London UK/ International Development Research Centre, Ottawa Canada.

Karamura, D., and Karamura, E. 1994. *A Provisional Checklist of Banana Cultivars in Uganda*. National Agricultural Research Organization (NARO) and INIBAP, Kampala, Uganda.

Karamura, D., and Mgenzi, B. 2004. On farm conservation of *Musa* diversity in the great lakes region of East Africa. *Afr. Crop Sci. J.* **12**(1): 75–83.

Karamura, D., Mgenzi, B., Karamura, E., and Sharrock, S. 2004. Exploiting indigenous knowledge for the management and maintenance of *Musa* biodiversity on farm. *Afr. Crop Sci. J.* **12**(1): 67–74.

Kastler, G. 2005. Europe's seed laws: locking out farmers. *Seedling*, July 2005. Grain Publications, Barcelona, Spain.

Kebebew, F., Tsehaye, Y., and McNeilly, T. 2001. Morphological and farmers cognitive diversity of barley (*Hordeum vulgare* L. [Poaceae]) at Bale and North Shewa of Ethiopia. *Genet. Resour. Crop Ev.* **48**(5): 467–481.

Keleman, A., Garcia Rano, H., and Hellin, J. 2009. Maize diversity, poverty, and market access: lessons from Mexico. *Dev. Pract.* **19**(2): 187–199.

Kennedy, G., and Burlingame, B. 2003. Analysis of food composition data on rice from a plant genetic resources perspective. *Food Chem.* **80:** 589–596.

Kenny, C. J. 2000. Expanding internet access to the rural poor in Africa. *Inform. Technol. Dev.* **9:** 25–31.

Kerimova, U. S. 2008. Virashivanie plodovikh kultur v fermerskikh khozyaistvakh. (Cultivation of fruit crops on farms). Ashgabat, Turkmenistan (in Russian).

Kesavan, P. C., and Swaminathan, M. S. 2008. Strategies and models for agricultural sustainability in developing Asian countries. *Phil. Trans. R. Soc. B.* **363:** 877–891.

Kimura, M., and Weiss, G. H. 1964. The stepping stone model of population structure and the decrease of genetic correlation with distance. *Genetics* **49:** 561–576.

Kitti, M., Heikkila, J., and Huhtala, A. 2009. Agrobiodiversity in poor countries. Price premiums deemed to miss multifaceted targets? **In:** *Agrobiodiversity, Conservation and Economic Development*. pp. 335–354. Kontoleon, A., Pascual, U. and Smale, M., Eds., Routledge Oxon, UK.

Kizito, E. B., Chiwona-Karltun, L., Egwang, T., Fregene, M., and Westerbergh, A. 2007. Genetic diversity and variety composition of cassava on small scale farms in Uganda: an interdisciplinary study using genetic markers and farmer interviews. *Genetica* **130:** 301–318.

Kontoleon, A., Pascual, U., and Smale, M. 2009. Introduction: agrobiodiversity for economic development: what do we know? Agrobiodiversity conservation and economic development. **In:** *Environmental Economics.* pp. 1–24. Kontoleon, A., Pascual, U., and Smale, M., Eds., Routledge Explorations, UK.

Kontoleon, A., Pascual, U., and Swanson, T. M. 2007. *Biodiversity Economics*. Cambridge University Press, UK.

Kouressy, M., Traoré, S., Vaksmann, M., Grum, M., Maikano, I., Soumaré, M., Traoré, P. S., Bazile, D., Dingkuhn, M., Sidibé, A., Bazile, D. and Weltzien, E. 2008. Adaptation of Malian sorghums to climate variability. *Cah. Agric.* **17**(2): 95–100.

Kremen, C., Williams, N., and Thorp, R. 2002. Crop pollination from native bees at risk 674 from agricultural intensification. *Proc. Nat. Acad. Sci.* **99:** 16812–16816.

Kruijssen, F., Keizer, M., and Giuliani, A. 2009. Collective action for small-scale producers of agricultural biodiversity products. *Food Policy* **34:** 46–52.

Kruiijssen, F., and Mysore, S. 2007. *Developing the Potential of Underutilized Fruits Through the Linkage of Farmers To The Market-A Case of Kokum Marketing in the Western Ghats of India.* Paper presented at the Third International Conference on Linking markets and farmers: exploring leading practices to foster economic growth in rural India, 11-15 March 2007, New Delhi, India.

Kruijssen, F., and Somsri, S. 2006. *Marketing Local Biodiversity in Thailand: Identification of a Possible Good Practices for On-Farm Biodiversity Management of Tropical Fruit Trees.* Presented at the Tropentag conference on International Agricultural Research for Development, 11-13 October 2006, Bonn, Germany.

Kumar, A. N., Balakrishnan, V., Girigan, G., and Raveendran, T. 2003. People's biodiversity registers: a case from India. **In:** *Conservation and Sustainable Use of Agricultural Biodiversity: A Source Book Vol I: Understanding Agricultural Biodiversity.* pp. 236–244. CIP-UPWARDS 2003 Eds., Los Banos, Philippines.

Kumar, P., Gupta, V. K., Misra, A. K., Modi, D. R., and Pandey, B. K. 2009. Potential of molecular markers in plant biotechnology. *Plant Omics J.* **2**(4): 141–162.

Lacy, S. M., Cleveland D. A. and Soleri, D. 2006. Farmer choice of sorghum varieties in Southern Mali. *Hum. Ecol.* **34**(3): 331–353.

Lapeña, I. 2008. *The Genetic Resources Policy Initiative in Peru*. Final report. Available at www.grpi.org

Latournerie-Moreno, L., Tuxill, J., Yupit-Moo, E., Arias-Reyes, L., Cristobal-Alejo, J., and Jarvis, D. I. 2006. Traditional maize storage methods of Mayan farmers in Yucatan, Mexico: implications for seed selection and crop diversity. *Biodivers. Conserv.* **15**(5) 1771–1795.

Laurentin, H. 2009. Data analysis for molecular characterization of plant genetic resources. *Gen. Res. Crop Evol.* **56:** 277– 292.

Lee, D. R. 2005. Agricultural sustainability and technology adoption: issues and policies for developing countries. *Amer. J. Agr. Econ.* **87**(5): 1325–1334.

Leskien, D., and Flitner, M. 1997. Intellectual property rights and plant genetic resources: options for a sui generis system. **In:** *Issues in Genet. Resour.* **6:** June 1997. Engler, J., Eds., International Plant Genetic Resources Institute. Rome, Italy.

Lewis, V., and Mulvany, P. M. 1997. *A Typology of Community Seed Banks*. NRI, UK.

Li, C., He, X., Zhu, S., Zhou, H., Wang, Y., Li, Y., Yang, J., Fan, J., Yang, J., Wang, G., Long, Y., Xu, J., Tang, Y., Zhao, G., Yang, J., Liu, L., Sun, Y., Xie, Y., Wang, H., and Zhu, Y. 2009 Crop diversity for yield increase. *PLoS ONE* **4**(11): 1–6. e8049. doi:10.1371/journal.pone.0008049.

Liang, L., and Brookfield, H. 2009. Sharing knowledge on agrodiversity for conservation and livelihood improvement. *LEISA Mag.* **25**(1): 23–25.

LI-BIRD. 2005 (unpublished). *Home Garden Donor Report Local Initiatives for Biodiversity Research and Development* (I-BIRD). Report to the Swiss Agency for Development and Cooperation, Home Garden Project, Bioversity International, Rome, Italy.

Lightfoot, C., Gillman, H., Scheuermeier, U., Nyimbo, V. 2008. The first mile project in Tanzania: linking smallholder farmers to markets using modern communication technology. *Mount. Res. Dev.* **28:** 13–17.

Lipper, L., Anderson, C. L., Dalton, T. J., and Keleman, A. 2010. Conclusions and policy implications. **In:** *Seed Trade in Rural Markets: Implications for Crop Diversity and Agricultural Development.* pp. 209–222. Lipper, L., Anderson, C.L. and Dalton, T.J., Eds., United National Food and Agricultural Organization (FAO), Rome, Italy.

Lipper, L., Cavatassi, R., and Hopkins, J. 2009. The role of crop genetic divesity in coping with drought: insights from eastern Ethiopia. **In:** *Agrobiodiversity, Conservation and Economic Development.* pp. 183–203. Kontoleon, A., Pascual, W. and Smale, M., Eds., Routeledge, London, UK.

Lipton, M. 2006. Can small farmers survive, prosper, or be the key channel to cut mass poverty*? Electron. J. Agric. Dev. Econ.* **3**(1): 58–85.

Loch, D. S., and Boyce, K. G. 2003. Balancing public and private sector roles in an effective seed supply system. *Field Crop Res.* **84:** 105–122.

Lopez, D. 2004. *Gender Relations as a Basis for Varietal Selection in Production Spaces in Yucatan, Mexico*. M.S. thesis, Wageningen University, The Netherlands.

Lopez Noriega, I. In press. Defensive protection of farmers' varieties. **In:** *Farmers' Varieties and Farmers' Rights: Addressing Challenges in Taxonomy and Law*. Halewood, M., Ed. Earthscan. London, UK.

Louette, D., Charrier, A., and Berthaud, J. 1997. *In situ* conservation of maize in Mexico: genetic diversity and maize seed management in a traditional community. *Econ. Bot.* **51:** 20–38.

Louwaars, N. 2000. Seed regulation and local seed systems. *Biotech. Dev. Monitor*, No. 42, June 2000.

Louwaars, N., Ed. 2002. *Seed Policy, Legislation and Law: Widening a Narrow Focus.* Food Products Press and Haworth Press, Binghamtom.

Louwaars, N., and Burgaud, F. In press. Variety registration: the evolution of registration systems with a special emphasis on agrobiodiversity conservation. **In:** *Farmers' Varieties and Farmers' Rights: Addressing Challenges in Taxonomy and Law*. Halewood, M., Ed. Earthscan. London, UK.

Magorokosho, C., Banziger, M., and Betran, F.J. 2006. Characterization of local maize landraces from Zimbabwe, Zambia and Malawi. **In:** *Enhancing Crop Genetic Diversity to Manage Abiotic Stress.* pp. 25–30. 23–27 May 2005, Budapest, Hungary. Jarvis D., Mar, I. and Sears L., Eds., Bioversity International, Italy, Rome.

Magurran, A. E. 2003. *Measuring Biological Diversity*. Blackwell, Oxford, UK.

Maharjan, S. K., Sigdel, E. R., Sthapit, B. R., and Regmi, B. R. 2010b. Tharu community's perception on climate changes and their adaptive initiations to withstand its impacts in Western Terai of Nepal. *Int. NGO J.* Vol 5: (accepted).

Maharjan, S. K., Subedi, A., Shrestha, P., Sthapit, B. R., Rana, R. B., and Gurung, A. R. 2010a. Enhancing conservation and use of agro-biodiversity on-farm through community seed bank in western Nepal. *Inst. Agric. Anim. Sci. J*. (*in press*).

Makokha, M., Omanga, P, Onyango, A., Otado, J., and Remington, T. 2004. Comparison of seed vouchers and fairs and direct seed distribution: lessons learned in Eastern Kenya and critical next steps, **In:** *Addressing Seed Security in Disaster Response: Linking Relief with Development.* pp. 44. Sperling, L., Remington, T., Haugen, J. M. and Nagoda, S., Eds., International Center for Tropical Agriculture, Cali, Colombia.

Mar, I. 2002. Safeguarding agricultural biodiversity on-farms in Hungary. **In:** *The Economics of Conserving Agricultural Biodiversity On-farm: Research Methods Developed from IPGRI's Global Project 'Strenghtening the Scientific Basis of In Situ Conservation of Agricultural Biodiversity.'* Smale, M., Mar, I., and Jarvis, D. I., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Mar, I., and Holly, L. 2000. Hungary. Adding benefits. **In:** *Conserving Agricultural Biodiversity In Situ: A Scientific Basis for Sustainable Agriculture.* pp. 194–198. Jarvis, D., Sthapit, B. and Sears, L., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Maredia, M., and Howard, J. 1998. *Facilitating Seed Sector Transformation in Africa: Key Findings from the Literature.* Food Security II Cooperative Agreement between U.S. Agency for International Development, Global Bureau, Economic Growth Center, Office of Agriculture and Food Security and Department of Agricultural Economics, Michigan State University. http://www.aec.msu.edu/fs2/polsyn/No33.htm.

Marquez, M., Valdes, N., Perez, D., Ferro, E. M., and Ortiz, R. 2009. Participatory plant breeding impact as part of the local agroinnovation by diffusing genetic diversity in agricultural sectors of Pinar del Rio. *Cultivos Tropicales* **30**(2): 18–23.

Marshall, D. R. 1977. The advantages and hazards of genetic homogeneity [Plant resistance to diseases]. *Ann. N. Y. Acad. Sci.* **287:** 1–20.

Martin, G. B., and Adams, M. W. 1987. Landraces of *Phaseolus vulgaris* (Fabacae) in northern Malawi. I. Regional variation. *Econ. Bot.* **41:** 190–203.

Maruyama, T., and Kimura, M. 1980. Genetic variability and effective population size when local extinction and recolonization of sub populations are frequent. *Proc. Nat. Acad. Sci.* **77:** 6710–6714.

Maurya, D. M., Bottrall, A., and Farrington, J. 1988. Improved livelihoods, genetic diversity and farmer participation: a strategy for rice breeding in rainfed areas of India. *Exp. Agric.* **24:** 311–320.

Mazhar, F. 2000. Seed conservation and management: participatory approaches of Naya Krishi seed network in Bangladesh. **In:** *Participatory Approaches to the Conservation and Use of Plant Genetic Resources.* pp: 149–153. Friis-Hansen, E. and Sthapit, B. R., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Mbabwine, Y., Sabiiti, E. N., Kiambin, D., and Mulumba, J. W. 2008. Ecogeographic genetic erosion, seed systems and conservation of plant genetic resources in Kabale highlands, Uganda. *Plant Genet. Resour. Newsl.* **156:** 33–41.

McGuire, S. J. 2007. Vulnerability in farmer seed systems: farmer practices for coping with seed insecurity for sorghum in Eastern Ethiopia. *Econ. Bot.* **61**(3): 211–222.

McGuire, S. J. 2008. Securing access to seed: social relations and sorghum seed exchange in eastern Ethiopia. *Hum. Ecol.* **36**(2): 217–229.

McGuire, S. J., Cleveland D. A., and Soleri, D. 2002. Farmers' views and management of sorghum diversity in Western Hareghe, Ethiopia: implications for collaboration with formal breeding. **In:** *Farmers, Scientists and Plant Breeding: Integrating Knowledge and Practice*. pp. 107–135. CABI Publishing, Wallingford, UK.

MEA. 2005. *Millennium Ecosystem Assessment, Ecosystems and Human Well-Being: Biodiversity Synthesis.* World Resources Institute, Washington, DC, USA.

Meinzen-Dick, R., and Eyzaguirre, P. 2009. Non-market institutions for agrobiodiversity conservation. **In:** *Agrobiodiversity, Conservation and Economic Development*. pp. 82–91. Kontoleon, A., Pascual, W., and Smale, M., Eds., Routeledge, London, UK.

Mekbib, F. 2008. Farmers' breeding of sorghum [*Sorghum bicolor* (L.) Moench] in the center of diversity, Ethiopia: II. Selection process, criteria and methods. *J. New Seeds* **9**(3): 234–265.

Mekbib, F. 2009a. Farmers as treasure chest of biodiversity: the case of sorghum (*Sorghum bicolor* (L.) Moench) in Ethiopia - a five decade analysis. *Maydica* **54**(1): 11–23.

Mekbib, F. 2009b. *Genetic Enhancement of Sorghum (Sorghum Bicolor (L.) Moench) Diversity Through an Integrated Approach.* Doctor of Philosphy (PhD) Thesis. Norwegian University of Life Sciences, Department of Plant and Environmental Sciences, Ås, Norway.

Mellas, H. 2000. Morocco. Seed supply systems: data collection and analysis. **In:** *Conserving Agricultural Biodiversity In Situ: A Scientific Basis for Sustainable Agriculture.* pp. 155–156. Jarvis, D. I., Sthapit, B. and Sears, L., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Mendum, R., and Glenna, L. L. 2010. Socioeconomic obstacles to establishing a PPB program for organic growers in the USA. *Sustainability* **2:** 79–91.

Meng, E., Taylor, J. E., and Brush, S. B. 1998. Implications for the conservations of wheat landraces in Turkey from an household model of varietal choice. **In:** *Farmers, Gene Banks & Crop Breeding: Economics Analyses of Diversity in Wheat, Maize and Rice*. Natural Resource Management and Policy series. pp. 127–142. Smale, M., Eds., Kluwer Academic, Boston, Massachusetts; Dordrecht, The Netherlands.

Mgonja, M. A., Subhash, C., Gwata, E. T., Obilana, A. B., Monyo, E.S., Rohrbach, D. D., Chisi, M., Kudita, S., and Saadan, H. M. 2005. Improving the efficiencies of national crop breeding programs through region-based approaches: the case of sorghum and pearl millet in southern Africa. *J. Food Agric. Environ.* **3**(3/4): 124–129.

Moore, G., and Tymowski, W. 2005. *Explanatory Guide to the International Treaty on Plant Genetic Resources for Food and Agriculture.* IUCN. Gland, Switzerland and Cambridge, UK.

Morales-Valderrama, C., and Quiñones-Vega, T. 2000. Social, cultural and economic data collection and analysis including gender: methods used for increasing access, participation and decision-making. **In:** *Conserving Agricultural Biodiversity In Situ: A Scientific Basis for Sustainable Agriculture.* pp. 49–50. Jarvis, D., Sthapit, B., and Sears, L., Eds.,International Plant Genetic Resources Institute, Rome, Italy.

Moseley, W. G., Carney, J., and Becker, L. 2010. Neoliberal policy, rural livelihoods and urban food security in West Africa: a comparative study of The Gambia, Côte d'Ivoire and Mali. *Proc. Nat. Acad. Sci.* **107**(13): 5774–5779.

Mujaju, C., and Chakauya, E. 2008. Morphological variation of sorghum landrace accessions on-farm in semi-arid areas of Zimbabwe. ANSInet, Asian Network for Scientific Information, Faisalabad, Pakistan. *Int. J. Bot.* **4**(4): 376–382.

Mujaju, C., Rusike, E., and Zinhanga, F. 2003. Community seedbank for semi-arid agriculture in Zimbabwe. **In:** *Conservation and Sustainable Use of Agricultural Biodiversity: A Source Book Vol I: Understanding Agricultural Biodiversity.* pp. 294–301. CIP-UPWARDS 2003 Eds., International Potato Centre (CIP) and User's Perspectives With Agricultural Research and Development (UPWARD), Los Banos, Philippines.

Mundt, C. C. 1991. Probability of mutation to multiple virulence and durability of resistance gene pyramids: Further comments. *Phytopathology* **81:**240–242.

Munyua, H., and Adera, E., Jensen, M. 2009. Emerging ICTs and their potential in revitalizing small scale agriculture in Africa. *Agric. Inform. Worldwide* **2:** 1–9.

Musa, T.M. 1998. *Farmer Seed System a Background Paper for the International Workshop on Developing Institutional Agreements and Capacity to Assist Farmers in Disaster Situations to Restore agricultural Systems and Seed Security Activities.* 3-5 November 1998. United National Food and Agricultural Organization (FAO), Rome, Italy.

Muthoni, J., and Nyamongo, D. O. 2008. Seed systems in Kenya and their relationship to on-farm conservation of food crops. *J. New Seeds* **9**(4): 330–342.

Nabban, G. P. 1989. *Cultures of Habitat: On Nature, Culture, and Story.* Counterpoint, Perseus Book Group, Washington, DC, USA.

Nagaranjan, S. 2007. Geographical indications and agriculture-related intellectual property rights issues. *Curr. Sci. India* **92:** 167–171.

Nagaranjan, L., Oliver King, E. D. I., Jones, H., and Vedhamoorthy, A. 2009. *Market Participation and Farmer Welfare: Case of Minor Millets in Pennagaram Market Hub, Dharmapuri District, India.* IFPRI, Washington, DC, USA.

Nagaranjan, L., Oliver King, E. D. I., Smale, M., and Dalton T. J. 2010. Access to minor millet genetic resources in rural market towns of Dharmapuri District, Tamil Nadu, India. **In:** *Seed Trade in Rural Markets*. pp. 125–145. Lipper, L., Anderson, C. L. and Dalton, T.J., Eds., United National Food and Agricultural Organization (FAO), Rome, Italy and Earthscan, London, UK.

Nagaranjan, L., and Smale, M. 2007. Local seed systems and village level determinants of millet crop diversity in marginal environments of Indai. *Euphytica* **155:** 167–182.

Nassif, F. 2002. Tuornee inter sites en faveur des femmes associees au project in situ Maroc. **In:** *La conservation In-Situ de la Biodiversite Agricole: Un Defi Puor Une Agriculture Durable*. Actes du Seminaire National Rabat, 21-22 Janvier 2002. pp. 349–355. Birouk, A., Sadiki, M., Nassif, F., Saidi, S., Mellas, H., Bammoun, A., and Jarvis, D., Eds., International Plant Genetic Resources Institute, Rome, Italy (in French).

Nassif, F., and Birouk, A. 2002. Tournee inter sites au profit des agriculteurs partenaires du project in situ Maroc. **In:** *La Conservation In-Situ de la Biodiversite Agricole: Un Defi Puor Une Agriculture Durable*. Actes du Seminaire National Rabat, 21 et 22 Janvier 2002. pp. 344–348. Birouk, A., Sadiki, M., Nassif, F., Saidi, S., Mellas, H., Bammoun, A. and Jarvis, D., Eds., International Plant Genetic Resources Institute, Rome, Italy (in French).

Nathaniels, N. Q. R. and Mwijage, A. 2006. *Seed Fairs And The Case Of Marambo Village, Nachingwea District, Tanzania: Implications of Local Informal Seed Supply and Variety Development for Research and Extension.* Network Paper No. 101. Agricultural Research and Extension Network (AgREN), Overseas Development Institute (ODI), UK.

Negri, V. 2003. Landraces in central Italy: where and why they are conserved and perspectives for their on-farm conservation. *Genet. Resour. Crop Ev.* **50:** 871–885.

Negri, V., Maxted, N., and Veteläinen, M., 2009. European landrace conservation: an introduction. **In:** *European Landraces on Farm Conservation, Management and Use.* pp. 1–22. Veteläinen M., Negri V., and Maxted N. Eds.,. Bioversity Technical Bulletin No. 15. Bioversity International. Rome, Italy.

Neuchatel Group. 2010. http://www.neuchatelinitiative.net/english/content_about.htm (*accessed 16 May 2010*)

Nkongolo, K. K., Chinthu, K. K. L., Malusi, M. and Vokhiwa, Z. 2008. Participatory variety selection and characterization of Sorghum (*Sorghum bicolor* (L.) Moench) elite accessions from Malawian gene pool using farmer and breeder knowledge. *Afr. J. Agric. Res.* **3**(4): 273–283.

Nuijten, E., and Almekinders, C. J. M. 2008. Mechanisms explaining variety naming by farmers and name consistency of rice varieties in The Gambia. *Econ. Bot.* **62**(2): 148–160.

OriGin. 2010. Organization for an International Geographical Indications Network http://www.origin-gi.com/

Okwu, O. J., and Umoru, B. I. 2009. A study of women farmers' agricultural information needs and accessibility: A case study of Apa local government area of Benue State, Nigeria. *Afr. J. Agric. Res.* **4**(12): 1404–1409.

Ortiz, R., Rios, H., Marquez, M., Ponce, M., Gil, V., Cancio, M., Chaveco, O., Rodriguez, O., Caballero, A., and Almekinders, C. 2009. Participatory plant breeding achievements evaluated by involved farmers. *Cultivos Tropicales* **30**(2): 106–112.

Østergård, H., Finckh, M. R., Fontaine, L., Goldringer, I., Hoad, S. P., Kristensen, K., Lammerts van B., Edith, T., Mascher, F., Munk, L., and Wolfe, M. S. 2009. Time for a shift in crop production: embracing complexity through diversity at all levels. *J. Sci. Food Agric.* **89**(9): 1439–1445(7).

Oude, L. A., and Carpentier, A. 2001. Damage Control Productivity: an input damage abatement approach. *J. Agric. Econ.* **52**(3): 11–22.

Oyedele, O., Yahaya, M. K. and Aldous, D. E. 2009. Citrus farmers' accessibility to horticultural information in South-Western Nigeria. *Acta Hortic.* **832:** 171–176.

Pascual U., and Perrings, C. 2007. Developing incentives and economic mechanisms for in situ biodiversity conservation in agricultural landscapes. *Agric. Ecosyst. Environ.* **121:** 256–268.

Platform for Agrobiodiversity Research, 2010. *The Use of Agrobiodiversity by Indigenous and Traditional Agricultural Communities in: Adapting to Climate Change.* Synthesis paper. PAR, Bioversity International, Rome, Italy. http://www.agrobiodiversityplatform.org/blog/wp-content/uploads/2010/05/PAR-Synthesis_low_FINAL.pdf (*accessed 28 May 2010*)

Peacock, J., and Chaudhury, A. 2002. The impact of gene technologies on the use of genetic resources. **In:** *Managing Plant Genetic Diversity.* pp.33–42. Engels, J. M. M., Rao, V. R., Brown, A. H. D., and Jackson, M. T., Eds., CABI Publishing, Wallingford, UK.

Perfecto, I., Vandermeerb, J., Mas, A. and Soto Pinto, L. 2005. Biodiversity, yield, and shade coffee certification. *Ecol. Econ.* **54:** 435–446.

Phiri, M. A. R., Chirwa, R., and Haugen, J. M. 2004. A review of seed security strategies in Malawi. **In:** *Addressing Seed Security in Disaster Response: Linking Relief with Development.* Sperling, L., Remington, T., Haugen, J. M., and Nagoda, S., Eds., International Center for Tropical Agriculture, Cali, Colombia. http://www.ciat.cgiar.org/africa/seeds.htm.

Pimbert, M. P., Boukary, B., and Holt-Giménez, E. 2010. Democratising research for food sovereignty in West Africa. *J. Peasant Stud.* **37**(1): 220–226.

Pingali, P. L., and Roger, P. A. 1995. *Impact of pesticides on farmers' health and the rice environment.* Kluwer, Dordrecht, The Netherlands.

Poudel, D., and Johnsen, F. H. 2009. Valuation of crop genetic resources in Kaski, Nepal: farmers' willingness to pay for rice landraces conservation. *J. Environ. Manage.* **90**(1): 483–491.

Poudel, D., Rijal, D., Johnsen, F. H., Synnevag, G., and Subedi, A. 2005. Conservation of crop genetic resources in community genebank: farmers' willingness to pay for conservation of rice landraces in Kaski, Nepal. **In:** *On-farm Conservation of Agricultural Biodiversity in Nepal. Volume 2: Managing Diversity and Promoting its Benefits.* pp. 149–160. Proceedings of the second national workshop, 25-27 August 2004, Nagarkot, Nepal. Sthapit, B. R., Upadhyay, M. P., Shrestha, P. K. And Jarvis, D. I., Eds., NARC, International Plant Genetic Resources Institute and LI-BIRD, Kathmandu, Nepal.

Poudel, D., Shrestha, P., Basnet, A., Shrestha, P., Sthapit. B., and Subedi, A. 2008. Dynamics of farmers' seed networks in rice seed flow systems: implications for on-farm conservation. pp. 88–96. **In:** *On-farm Management of Agricultural Biodiversity in Nepal: Lessons Learned.* Proceedings of the National Symposium 18-19 July 2006, Kathmandu, Nepal. Sthapit, B. R., Gauchan, D., Subedi, A. and Jarvis, D., Eds., Bioversity International, Rome Italy.

Pradhan N., Providoli, I., Regmi, B., and Kafle, G. 2010. Valuing water and its ecological services in rural landscapes: a case study from Nepal. *Mount. Forum Bull.* January 2010: 32–34.

Pradhanang, P. M., and Sthapit, B. R. 1995. Effect of cultivar mixtures on yellow rust incidence and grain yield of barley in the hills of Nepal. *Crop Prot.* **14**(4):331–334.

Prasanna, B. M., Rao, S. K., Gautam, K., and Singh, R. B. 2008. "Varieties of common knowledge" in the context of plant variety protection. *Curr. Sci. India* **95:** 1522–1524.

Pressoir, G., and Berthaud, J. 2004. Patterns of population structure in maize landraces from the Central Valleys of Oaxaca in Mexico. *Heredity* **92:** 88–94.

Pretty, J. 2002. *Agri-culture: Reconnecting People, Land and Nature.* Earthscan, London, UK.

Pretty, J. 2008. Agricultural sustainability: concepts, principles and evidence. *Phil. Trans. R. Soc. B.* **363:** 447–465.

Pretty, J. and Smith, D. 2004. Social capital in biodiversity conservation and management. *Conserv. Biol.* **18**(3): 631–638.

Quiros, C. F., Brush, S. B., Douches, D. S., Zimmerer, K. S. and Huestis, G. 1990. Biochemical and folk assessment of variability of Andean cultivated potatoes. *Econ. Bot.* **44**(2): 254–266.

Ramakrishnappa, K. 2006. Geographical indications: a legal tool for protection of traditional varieties. *Biomed.* **1:** 91–93.

Ramirez, M. 2001. *Adventures in Agrobiodiversity, Ecotourism for Agrobiodiversity Conservation, a Feasibility Study.* Instituto Internacional de Recursos Fitogeneticos, Cali, Colombia.

Ramirez, M., Nicklin, C., Williams, D. E., Williams, K. A., Tapia, C., and Carrera, V. H. 2009. *Promotion of Andean Crops for Rural Development in Ecuador*. Mountain Forum, Lima, Peru. On line:http://www.mtnforum.org/rs/ol/searchft.cfm?step=vd&docid=4225 (*accessed 16 May 2010*).

Ramirez, M., and Williams, D. E. 2003. *Guía Agro-Culinaria de Cotacachi, Ecuador y Alrededores*. Instituto Internacional de Recursos Fitogeneticos, Cali, Colombia (in Spanish).

Ramprasad, V. 2003. Millet conservation in Southern India. **In:** *Conservation and Sustainable Use of Agricultural Biodiversity: Source Book Vol II: Strengthening Local Management of Agricultural Biodiversity.* pp. 362–367. CIP-UPWARDS 2003 Eds., International Potato Centre (CIP) and User's Perspectives With Agricultural Research and Development (UPWARD), Los Banos, Philippines.

Ramprasad, V. 2009. Community seed banks for maintaining genetic diversity. *LEISA Mag. Low Ext. Imput Sustain. Agric.* **23**(2): 20–21.

Rana, R. B. 2004. *Influence of Socio-Economic and Cultural Factors on Aagrobiodiversity Conservation on-Farm in Nepal.* PhD Thesis, The University of Reading, UK.

Rana, R. B., Garforth, C., Jarvis, D., and Sthapit, B. 2007a. Influence of socioeconomic and cultural factors in rice varietal diversity management on-farm in Nepal. *Agric. Hum. Values* **24**(4): 461–472.

Rana, R. B., Garforth, C., and Sthapit, B. R. 2008. Farmers' management of rice varietal diversity in the mid hills of Nepal: Implications for on-farm conservation and crop improvement. *Plant Genet. Resour. Charact. Utiliz.* **28:** 1–14.

Ravi, S. B. 2009. *The Conflict Between Seed Bill and PPVFR Act of India: Lessons for Other South Asian Countries.* Policy Brief. No. 19, Kathmandu, South Asia Watch on Trade, Economy and Environment (SAWTEE), Nepal.

Regine, A. 2005 *Results from an International Stakeholder Survey on Farmers' Rights*, FNI Report 9/2005. The Fridtjof Nansen Institute, Lysaker, Norway.

Remington, T., Walsh, S., Charles, E., Maroko, J., and Omanga, P. 2002. Getting off the seeds-and-tools treadmill with CRS seed vouchers and fairs. *Disasters* **26**(4): 316–328.

Renard, M. C. 2003, Fair trade: quality, market and conventions. *J. Rural Stud.* **19:** 87–96.

Rhouma, A., Nasr, N., Zirari, A., and Belguedj, M. 2006. Indigenous knowledge in management of abiotic stress: date palm geneticresources diversity in the oases of Maghreb region. **In:** *Enhancing the Use of Crop Genetic Diversity to Manage Abiotic Stress in Agricultural Production Systems*. *23-27 May, Budapest, Hungary*. pp. 55–61. Jarvis, D., Mar, I., and Sears, L., Eds., Bioversity International, Rome, Italy.

Richards, P., and Ruivenkamp, G. 1997. *Seeds and Survival: Crop Genetic Resources in War and Reconstruction in Africa*. International Plant Genetic Resources Institute, Rome, Italy.

Richards, A. 2001. Does low biodiversity resulting from modern agricultural practice affect crop pollination and yield? *Ann. Bot.* **88:** 165–172.

Richards, P., De Bruin-Hoekzema, M., Hughes, S. G., Kudadjie-Freeman, C., Offei, S., Struik, P. and Zannou, A. 2009. Seed systems for African food security: linking molecular genetic analysis and cultivator knowledge in West Africa. *Int. J. Technol. Manage.* **45**(1-2): 196–214.

Rijal, D. K. 2007. *On-farm Conservation and Use of Local Crop Diversity: Adaptations of Taro (Colocasia esculenta) and Rice (Oryza sativa) Diversity to Varying Ecosystems of Nepal.* Ph. D Thesis. University of Life Science (UMB), Norway.

Rijal, D., Rana, R., Subedi, A., and Sthapit, B. 2000. Adding value to landraces: community-based approaches for *in situ* conservation of plant genetic resources in Nepal. **In***: Participatory Approaches to the Conservation and Use of Plant Genetic Resources.* pp. 166–172. Friis-Hansen, E. and Sthapit, B., Eds., International Plant Genetic Resources Institute, Rome Italy,

Ríos, H. 2009. Participatory seed dissemination: some field experiences. *Cultivos Tropicales* **30**(2): 89–105.

Robbert, P., van der Steeg, R. P., Remington, T., Grum, M., and Kemigisha, E. 2004. Seed vouchers and fairs and agrobiodiversity in Western Uganda. **In:** *Addressing Seed Security in Disaster Response: Linking Relief with Development.* pp. 29–43. Sperling, L., Remington, T., Haugen, J. M. and Nagoda, S., Eds., International Center for Tropical Agriculture, Cali, Colombia.

Robertson, G. P., and Swinton, S. M. 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. *Front. Ecol. Environ.* **3**(1): 38–46.

Rohrbach, D., and Kiala, D. 2007. Development options for local seed systems in Mozambique. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, *J. SAT Agric. Res.* **3**(1): 1–29.

Rohrbach, D. D., Mtenga, K., Kiriwaggulu, J. A. B., Monyo, E. S., Mwaisela, F., and Saadan, H. M. 2002. *Comparative Study of Three Community Seed Supply Strategies in Tanzania.* International Crop Research Institute for the Semi-Arid Tropics, Bulawayo, Zimbawe.

Ruiz, M. 2009. *Agrobiodiversity Zones and the Registry of Native Crops in Peru: Learning from Ourselves.* Bioversity International and Sociedad Peruana de Derecho Ambiental, Lima, Peru.

Rusike, E., Mujaju, C., Mafa, A., and Zinhanga, F. 2003. Increasing seed diversity through community seed fairs in Zimbabwe. **In:** *Conservation and Sustainable Use of Agricultural Biodiversity: A Source Book Vol I: Understanding Agricultural Biodiversity.* pp. 277–283. CIP-UPWARDS 2003 eds. International Potato Centre (CIP) and User's Perspectives with Agricultural Research and Development (UPWARD), Los Banos, Philippines.

Sadiki, M. 2006. Diversity of Moroccan local faba bean landraces for reaction to drought stress. **In:** *Enhancing Crop Genetic Diversity to Manage Abiotic Stress.* pp. 11–17. 23-27 May 2005, Budapest, Hungary. Jarvis, D., Mar, I., and Sears, L., Eds., Bioversity International, Italy, Rome.

Sadiki, M., Belqadi, L., Mahdi, M., and Jarvis, D. 2001. Identifying units of diversity management by comparing traits used by farmers to name and distinguish faba bean (*Vicia faba* L.) cultivars with measurements of genetic distinctiveness in Morocco. **In:** *Proceedings of the legumed Symposium "Grain Legumes in the Mediterranean Agriculture,"* October 25–27, 2001, Rabat, Morocco.

Sadiki, M., Birouk, A., Bouizzgaren, A., Belqadi, L., Rh'rrib, K., Taghouti, M., Kerfal, S., Lahbhili, M., Bouhya, H., Douiden, R., Saidi, S., and Jarvis, D. 2002. La diversité génétique in situ du blé dur, de l'orge, de la luzerne et de la fève: Options de stratégie pour sa conservation. **In:** *La conservation In-Situ de la Biodiversite Agricole: Un Defi Puor Une Agriculture Durable*. Actes du Seminaire National Rabat, 21 et 22 Janvier 2002. pp. 37–117. Birouk, A., Sadiki, M., Nassif, F., Saidi, S., Mellas, H., Bammoun, A. and Jarvis, D., Eds., International Plant Genetic Resources Institute, Rome, Italy (in French).

Sadiki, M., and Jarvis, D. 2005. Conservation *in situ* de la diversité génétique des clutures par sa gestion à la ferme dans les agro écosystèmes marocains. *Les Actes du BRG* **1:** 347–357 (in French).

Sadiki, M., Jarvis, D., Rijal, D., Bajracharya, J., Hue, N. N., Camacho, T. C., Burgos-May, L. A., Sawadogo, M., Balma, D., Lope, D., Arias, L., Mar, I., Karamura, D., Williams, D., Chavez-Servia, J., Sthapit, B., and Rao, V. R. 2007. Variety names: an entry point to crop genetic diversity and distribution in agroecosystems? **In:** *Managing Biodiversity in Agricultural Ecosystems.* pp. 34–76. Jarvis, D. I., Padoch, C., and Cooper, D., Eds., Columbia University Press, New York, USA.

Sagnard, F., Barnaud, A., Deu, M., Barro, C., Luce, C., Billot, C., Rami, J. F., Bouchet, S., Dembele, D., Pomies, V., Calatayud, C., Rivallan, R., Joly, H., vom Brocke, K., Toure, A., Chantereau, J., Bezancon, G., and Vaksmann, M. 2008. Multi-scale analysis of sorghum genetic diversity: understanding the evolutionary processes for *in situ* conservation. (Special issue: Agrobiodiversites). *Cah. Agric.* **17**(2): 114–121.

Salazar, R., Louwaars, N. P., and Visser, B. 2007. On protecting farmers' new varieties: new approaches to rights on collective innovations in plant genetic resources. *World Dev.* **35:** 1515–1528.

Salick, J., Cellinese, N., and Knapp, S. 1997. Indigenous diversity of Cassava: generation, maintenance, use and loss among the Amuesha, Peruvian upper Amazon. *J. Econ. Bot.* **51**(1): 6–19.

Satheesh, P. V. 2000. Linking to community development: using participatory approaches to in situ conservation. **In:** *Participatory Approaches to the Conservation and Use of Plant Genetic Resources.* Friis-Hansen, E., and Sthapit, B. R., eds., International Plant Genetic Resources Institute, Rome.

Sawadogo, M., Balma, D., Some, L., Fadda, C. and Devra, J. 2006. Management of the agrobiodiversity under the clinal variation of rainfall pattern in Burkina Faso: the example of okra drought resistance. **In:** *Enhancing Crop Genetic Diversity to Manage Abiotic Stress*. pp. 18–24. 23-27 May 2005, Budapest, Hungary. Jarvis D., Mar, I. and Sears L., Eds., Bioversity International, Italy, Rome.

Sawadogo, M., Ouedraogo, J., Belem, M., Balma, D., Dossou, B., and Jarvis, D. I. 2005. Components of the ecosystem as instruments of cultural practices in the in situ conservation of agricultural biodiversity. *Plant Genet. Resour. Newsl.* **141:** 19–25.

Scarcelli, N., Tostain, S., Baco, M. N., Agbangla, C., Dainou, O., Vigouroux, Y. and Pham, J. L., Maxted, N., Ford-Lloyd, B. V., Kell, S. P., Iriondo, J. M., Dulloo, M. E. and Turok, J. 2007. Does agriculture conflict with *in situ* conservation? A case study on the use of wild relatives by yam farmers in Benin. **In:** *Crop Wild Relative Conservation and Use.* pp. 331–339. CABI Publishing, Wallingford, UK.

Scarcelli, N., Tostain, S., Vigouroux, Y., Agbangla, C., Daïnou, O., and Pham, J. L. 2006. Farmers' use of wild relative and sexual reproduction in a vegetatively propagated crop. The case of yam in Benin. *Mol. Ecol.* **15:** 2421–2431.

Scheidegger, U., and Prain, G. 2000. Support to diversity in potato seed supply. **In:** *Encouraging Diversity – The Conservation and Development of Plant Genetic Resources.* pp. 232–236. Almekinders, C.and de Boef, W., eds., Intermediate Technology Publications, London, UK.

Schumann, G. L. 1991. *Plant Diseases: Their Biology and Social Impact.* APS Press, St. Paul, Minnesota, USA.

Sedjo, R. A., and Swallow, S. K. 2002. Voluntary eco-labeling and the price premium. *Land Econ.***78**(2): 272–284.

Shah, A. A., and Tripathi, R. B. 2009. Effective agricultural information sources for contact and non contact farmers under T and V system of extension in Kashmir. *Asian J. Home Sci.* **4**(1): 64–66.

Shalpykov, K. 2008. Sovremennoe sostoyaniye I perspective izucheniya prioritetnikj plodovikh kultur v Kyrgyzstane (Current status and prospects of study of priority fruit crops in Kyrgyzstan). *Vestnik of Kyrgyz Technical University* (in Russian), Kyrgyzstan.

Shrestha, R. R. 2009. Rainwater harvesting and groundwater recharge for water storage in the Kathmandu valley. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, ICIMOD. *Sustain. Mount. Dev.* **56:** 27–30.

Shrestha, R. R., Pitamber, S., Maharjan, S. K., and Sthapit, B. R. 2010. *Participatory Seed Exchange to Enhance Conservation and Use of Genetic Resources in Home Garden.* Paper presented at the National Workshop on Home Garden of Nepal. Kathmandu, Nepal.

Shrestha, P., Subedi, A., Sthapit, S., Rijal, D., Gupta, S. K., Sthapit, B. 2006. Community seed bank: reliable and effective option for agricultural biodiversity conservation. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K., and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Sillitoe, P. 2003. The gender of crops in the Papua New Guinea highlands. **In:** *Women and Plants, Gender Relations in Biodiversity Management and Conservation.* pp. 165–180. Howard, P., Eds., Zed Books, NY, USA.

Singh, I. P. 2010. National Research Centre for Citrus (NRCC, Nagpur India), pers. comm.

Sismanto, Y. 2003. Rediscovering local rice for improved food security in Indonesia. **In:** *Conservation and Sustainable Use of Agricultural Biodiversity: A Source Book Vol I: Understanding Agricultural Biodiversity.* pp. 177–182. CIP-UPWARDS 2003 eds. International Potato Centre (CIP) and User's Perspectives with Agricultural Research and Development (UPWARD), Los Banos, Philippines.

Siudek, T. 2008. Regional economic development: theory and practice in Poland economic science for rural development. **In:** *Economic Science for Rural Development.* Proceedings of the International Scientific Conference on Finances, Taxes, Investment and Support Systems **17:** 136–144. Jelgava, Lettonia. (http://ef.llu.lv/files/p2/Finances_Taxes_Investment_and_Support_Systems_17_1.pdf#page=135 *accessed May 8 2010*).

Slatkin, M. 1991. Inbreeding coefficients and coalescence times. *Genet. Res.* **58**(2): 167–175.

Slootweg, R., Kolhoff, A, Verheem, R., and Hoft, R., 2006. *Biodiversity in EIA and SEA.* Background Document to CBD Decision VIII/28. Voluntary Guidelines on Bioversity-Inclusive Impact Assessment. Secretariat of the Convention on Biological Diversity. Montreal, Canada.

Smale, M., 2006. *Valuing Crop Biodiversity: On-Farm Genetic Resources and Economic Change.* CABI Publishing, Wallingford, UK.

Smale, M., Bellon, M., and Aguirre A. 2001. Maize diversity, variety attributes, and farmers' choices in southeastern Guanajuato, Mexico. *Econ. Dev. Cult. Change* **50**(1): 201–225.

Smale, M., Bellon, M. R., Jarvis, D., and Sthapit, B. 2004. Economic concepts for designing policies to conserve crop genetic resources on-farms. *Genet. Resour. Crop Ev.* **51:** 121–135.

Smale, M., Cohen, M. J., and Nagarajan, L. 2009. *Local Markets, Local Varieties: Rising Food Prices and Small Farmers' Access to Seed.* Issue Brief 59, IFPRI, Washington, DC, USA.

Smale, M., Diakité, L., and Grum, M. 2009. *Mali: Millet and Sorghum seed in the Sahel.* IFPRI, Washington, DC, USA.

Smale, M., Diakité, L., and Grum, M. 2010. When grain markets supply seed: village markets for millet and sorghum in the Malian Sahel. **In:** *Seed Trade in Rural Markets: Implications for Crop Diversity and Agricultural Development.* pp. 53–74. Lipper, L., Anderson, C. L., and Dalton, T. J., Eds., United National Food and Agricultural Organization (FAO), Rome, Italy.

Smale, M., Diakite, L., Sibide, A., Grum, M., Jones, H., Traore, I.S., and Guindo, H. 2008. *The Impact of Farmer Participation in Diversity Field Flora, Mali*. Discussion Paper 746. IFPRI, Washington, DC, USA.

Smale, M., and King, A. 2005. *Genetic Resource Policies: What Is Diversity Worth to Farmers?* Briefs 13-18. International Plant Genetic Resources Institute and IFPRI.

Smale, M., Lipper, L., and Koundouri, P. 2006. Scope, limitation and furture directions. **In:** *Valuing Crop Biodiversity, On Farm Genetic Resources and Economic Change.* pp 280–295. Smale, M., Eds., CABI Publishing, Wallingford, UK.

Smith, B. G., Pollock, C., Pretty, J., Crute, I., Leaver, C., and Dalton, H. 2008. Developing sustainable food supply chains. Philosophical transactions of the Royal Society of London. *Biol. Sci. Series B* **363:** 849–861.

Smolders, H., and Caballeda, E. 2006. *Field Guide for Participatory Plant Breeding in Farmer Field Schools.* CGN, the Netherlands, Eds., 136 pp, PEDIGREA publication.

Song, Y., and Jiggins, J. 2003. Women and maize breeding: the development of new seed systems in a marginal area of South-west China. **In:** *Women and Plants, Gender Relations in Biodiversity Management and Conservation.* pp. 273–287. Howard, P., Eds., Zed Books, NY, USA.

Sperling, L., Ashby, J. A. Q., Smith, M. E., Weltzien, E., and McGuire, S. 2001. A framework for analyzing participatory plant breeding approaches and results. *Euphytica* **122:** 439–450.

Sperling, L., and Cooper, H. D. 2006. Understanding seed system and strengthening seed security: a background paper. **In:** *Towards Effective and Sustainable Seed Relief Aactivities.* United National Food and Agricultural Organization (FAO) plant production and protection paper 181. Rome, Italy.

Sperling, L, Cooper, H. D., and Remington, T. 2008. Moving towards more effective seed aid. *J. Dev. Stud.* **44**(4): 586–612.

Sperling, L., and Mcguire, S. 2010. Understanding and strengthening informal seed markets. *Expl. Agric.* **46**(2): 119–136.

Srinivasan, C.S., 2003. Exploring the feasibility of farmers' rights. *Dev. Policy Rev.* **21**(4): 419–447.

Sthapit, B. 1998. Nepal 'diversity fair' inspires community. Geneflow, International Plant Genetic Resources Institute, Rome, Italy.

Sthapit, B. 1999. Nepal 'poets and farmers unite in Nepal to save native crops'. p.25. Geneflow, International Plant Genetic Resources Institute, Rome, Italy.

Sthapit, B. R., Joshi, K. D., Rana, R. B., Upadhayay, M. P., Eyzaguirre, P., and Jarvis, D. 2000. Enhancing biodiversity and production throught participatory plant breeding: setting breeding goals. **In:** *An Exchange of Experiences from South and South Est Asia.* Proceedings of the International Symposium on Participatory Plant genetic Resource Enhancement, Pokhara, Nepal, 1-5 May 2000. International Center for Tropical Agriculture, PRGA Program, Cali, Colombia.

Sthapit, B., Gautam, R., Gyawali, S., Joshi, B. K., Subedi, A., Yadav, R. B., Chaudhary, P., and Rijal, D. 2006d. Diversity kits: deploying new diversity to farmers. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K. and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Sthapit, B. R., Joshi, K. D., and Witcombe, J. R. 1996. Farmer participatory crop improvement. III: participatory plant breeding, a case study for rice in Nepal. *Exp. Agric.* **32:** 479–496.

Sthapit, B. R., and Quek, P. 2005. Community biodiversity register: overview, concepts and some systematic approaches. **In:** *Learning from Community Biodiversity Register in Nepal.* Proceedings of the National Workshop 27-28 Oct 2005, Khumaltar, Nepal. Subedi, A., Sthapit, B., Upadhyay, M. P. and Gauchan, D., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Sthapit, B., Rana, R., Eyzaguirre, P., and Jarvis, D. 2008a. The value of plant genetic diversity to resource-poor farmers in Nepal and Vietnam. *Int. J. Agric. Sustain.* **6**(2): 148–166.

Sthapit, B., Rana, R. B., Subedi, A., Gyawali, S., Bajracharya, J., Chaudhary, P., Joshi, B. K., Sthapit, S., Joshi, K. D., and Upadhyay, M. P. 2006b. Participatory four cell analysis (FCA) for local crop diversity. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K., and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Sthapit, B. R., and Rao, V. R. 2009. Consolidating community's role in local crop development by promoting farmer innovation to maximise the use of local crop diversity for the well-being of people. *Acta Hort.* **806:** 669–676; http://www.actahort.org/books/806/806_83.htm.

Sthapit, B. R., Rijal, D., De, N. N., and Jarvis, D. 2003a. A role for diversity fairs: experiences from Nepal and Vietnam. **In:** *Conservation and Sustainable Use of Agricultural Biodiversity: A Source Book Vol II: Strengthening Local Management of Agricultural Biodiversity.* pp. 271–276. CIP-UPWARDS 2003, Eds., Los Banos, Philippines.

Sthapit, B., Shrestha, P., Baral, K. P., Subedi, A., Bajracharya, J., Yadav, R. B. 2006c. Diversity block: assessing and demonstrating local crop diversity. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K. and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Sthapit, B. R., Shrestha, P. K., Subedi, A., Shrestha P., Upadhyay, M. P., and Eyzaguirre, P. 2008b. Mobilizing and empowering community in biodiversity management. **In:** *Farmer's Varieties and Seeds. Supporting Informal Seed Supply in Ethiopia.* pp.160–166. Thijssen, M. H., Bishaw, Z., Beshir, A., and de Boef, W. S., Eds., Wageningen International, Wageningen, The Netherlands.

Sthapit, B. R., Shrestha, P. K., and Upadhyay, M. P., Eds. 2006a. *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Sthapit, B. R., Subedi, A., Gyawali, S., Jarvis, D., and Upadhaya, M. P. 2003b. *In situ* conservation of agricultural biodiversity through participatory plant breeding in Nepal. **In:** *Conservation and Sustainable Use of Agricultural Biodiversity: A Source Book Vol II: Strengthening Local Management of Agricultural Biodiversity.* pp. 311–321. CIP-UPWARDS 2003, Eds., Los Banos, Philippines.

Sthapit, B. R., Subedi, A., Rijal, D., Rana, R., and Jarvis, D. 2003d. Strengthening community-based on-farm conservation of agricultural biodiversity: experiences from Nepal. **In:** *Conservation and Sustainable Use of Agricultural Biodiversity: A Source Book Vol II: Strengthening Local Management of Agricultural Biodiversity.* pp. 344–354. CIP-UPWARDS 2003, Eds., Los Banos, Philippines.

Sthapit, B. R., Subedi A., Shrestha P., Shrestha P. K., and Upadhyay M. P. 2008c. Practices supporting community management of farmers' varieties. 2008. **In:** *Farmer's Varieties and Seeds. Supporting Informal Seed Supply in Ethiopia.* pp.166–171. Thijssen, M. H., Bishaw, Z., Beshir, A. and de Boef, W. S., Eds., Wageningen International, Wageningen, The Netherlands.

Sthapit, B. R., Upadhyay, M. P., Baniya, B. K., Subedi, A., and Joshi, B. K. 2003e. *On Farm Management of Agricultural Biodiversity in Nepal.* Proceedings of a National workshop, 24-26 April 2001, Lumle, Nepal. International Plant Genetic Resources Institute, LI-BIRD and NARC, Eds., Kathmandu, Nepal.

Steele, K. A., Edwards, G., Zhu, J., and Witcombe, J. R. 2004. Marker-evaluated selection in rice: shifts in allele frequency among bulks selected in contrasting agricultural environments identify genomic regions of importance to rice adaptation and breeding. *Theor. Appl. Genet.* **109:** 1247–1260.

Steele, K. A., Virk, D. S., Kumar, R., Prasad, S. C., and Witcombe, J. R. 2004. Field evaluation of upland rice lines selected for QTLs controlling root traits. *Field Crop Res.* **101**(2007): 180–186.

Strange, R. N., and Scott, P. R. 2005. Plant disease: a threat to global food security. *Ann. Rev. Phytopathology* **43:** 83–116.

Subedi, A., Chaudhary, P., Baniya, B., Rana, R., Tiwari, R., Rijal, D., Jarvis, D. and Sthapit, B. 2003. Who maintains crop genetic diversity and how: implications for on-farm conservation and utilization. *Cult. Agric.* **25**(2): 41–50.

Subedi, A., and Garforth, C. 1996. Gender information and communication networks: implications for extension. *Eur. J. Agric. Educ. Exten.* **3**(2): 63–74.

Subedi, A., Sthapit, B., Rijal, D., Gauchan, D., Upadhyay, M. P., and Shrestha, P. K. 2006. Community biodiversity register: consolidating community role in management of agricultural biodiversity. **In:** *Good Practices: On-farm Management of Agricultural Biodiversity in Nepal.* Sthapit, B. R., Shrestha, P. K., and Upadhyay, M. P., Eds., NARC, LI-BIRD, International Plant Genetic Resources Institute and IDRC, Kathmandu, Nepal.

Sunwar, S., Baral, K. P., Joshi, M., Basnet, B. M. S., Gyawali, S., Subedi, A., Upadhayay, M. P., Shrestha, P. K., and Sthapit, B. R. 2005. Developing resource guide book on agrobiodiversity for secondary school. **In:** *On-farm Conservation of Agricultural Biodiversity in Nepal. Vol II. Managing Diversity and Promoting its Benefits.* Proceedings of the Second National Workshop 25-27 August 2004, Nagarkot, Nepal. Sthapit, B. R., Upadhyay, M. P., Shrestha, P. K. and Jarvis D., Eds., International Plant Genetic Resources Institute, NARC, LI-BIRD, Kathmandu, Nepal.

Sunwar, S., Basnet, L. K., Khatri, C., Subedi, M., Shrestha, P., Gyawali, S., Bhandari, B., Gautam, R., and Sthapit, B. 2007. Consolidating farmer's roles in participatory maize breeding in Nepal. **In:** *Bringing Farmers Back into Breeding Experiences with PPB and Challenges for Institutionalisation.* Almekinders, C. J. M., Hardon, J. with Christink, A., Humphries, S., Pelegrina, D., Sthapit, B., Vernooy, R., Visser, B., and Weltzien, E., Eds., AgroSpecial 5, Agromisa Wageningen, The Netherlands.

Swallow, S. K., and Sedjo, R. A. 2000. Eco-labeling consequences in general equilibrium: a graphical assessment. *Land Econ.* **76:** 28–36.

Swaminathan, M. S. 2000. Government-industry-civil society: partnerships in integrated gene management. Volvo environment prize lecture 1999. *Ambio* **29:** 115–121.

Swaminathan, M. S. 2001. Community grain bank movement. **In:** *Community Grain Bank- an Instrument for Local Food Security.* pp. 11–15. Swaminathan, M. S. Research Foundation and World Food Programme, Chennai, India.

Swaminathan, M. S. 2003. Towards an evergreen revolution in agriculture: technology, planning nd management. *Rites J.* **7:** 1–14.

Swanson, T. 1996. Global values of biological diversity: the public interest in the conservation of plant genetic resources for agriculture. *Plant Genet. Resour. Newsl.* **105:** 1–7.

Swanson, T., and Goschl, T. 2000. Property rights issues involving plant genetic resources: implications of ownership for economic efficiency. *Ecol. Econ.* **32:** 75–92.

Swift, M.J., Izac, A. M. N., and van Noordwijk, M. 2004. Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? *Agric. Ecosyst. Environ.* **104:** 113–134.

Taghouti, M., and Saidi, S. 2002. Perception et désignation des entités de blé dur gérées par les agriculteurs. **In:** *La Conservation in Situ de la Biodiversité Agricole: Un Défi pour une Agriculture Durable.* pp. 275–279. Birouk, A., Sadiki, M., Nassif, F., Saidi, S., Mellas, H., Bammoune, A. and Jarvis, D., Eds., International Plant Genetic Resources Institute, Rome, Italy (in French).

Tahiri, A., 2005. Seed systems in Morocco. **In:** *Seed Systems and Crop Genetic Diversity On-Farm*. Proceeding of a Workshop, 16-20 September 2003, Pucallpa, Peru. pp. 133–139. Jarvis, D. I., Sevilla-Panizo, R., Chavez-Servia, J. L. and Hodgkin, T., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Tanto, T. H., Ra, D., Bitocchi, E., and Papa, R. 2009. Genetic diversity of barley (*Hordeum vulgare L.)* landraces from the central highlands of Ethiopia: comparison between the Belg and Meher growing seasons using morphological traits. *Genet. Resour. Crop Ev.* **56:** 1131–1148.

Tapia, M. E. 2000. Mountain agrobiodiversity in Peru: Seed fairs, seed banks, and mountain-to-mountain exchange. *Mount. Res. Dev.* **20:** 220–225.

Tapia, M. E., and De la Torre, A. 1998. *Women Farmers and Andean Seeds. Gender and Genetic Resources Management.* International Plant Genetic Resources/United Nations, Food and Agricultural Organization (FAO), Rome, Italy.

Tapia, M. E., and Rosa, A. 1993. Seed fairs in the Andes: a strategy for local conservation of plant genetic resources. **In:** *Cultivating Knowledge: Genetic Diverity, Farmer Participation and Crop Research.* pp. 111–118. de Boef. W., Amanor, K., Wellard, K. and Beddington, A., Eds., IT Publications, UK.

Teshome, A., Baum, B. R., Fahrig, L., Torrance, J. K., Arnason, T. J., and LAmbert, J. D. 1997. Sorghum (*Sorghum bicolor* (L.) Moench) landrace variation and classification in north Shewa and south Welo regions of Ethiopia. *Euphytica* **97:** 255–263.

Teshome, A., Brown, A. H. D., and Hodgkin, T. 2001. Diversity in landraces of cereal and legume crops. *Plant Breeding Rev.* **21:** 221–261.

Teshome, A., Torrance, J.K., Lamber, J. D. H., Fahrig, L., Baum, B. R., and Arnason, J. T. 1999. Traditional farmers' knowledge or sorghum (*Sorghum biocolor* [Poaceae]) landrace storability in Ethiopia. *Econ. Bot.* **53:** 69–78.

Thamaga-Chitja, J. M., Hendriks, S. L., Ortmann, G. F. and Green, M. 2004. Impact of maize storage on rural household food, security in Northern Kwazulu-Natal. *J. Fam. Ecol. Cons. Sci.* **32:** 8–15. http://ajol.info/index.php/jfecs/article/viewFile/52843/41445 (*accessed 16 May 2010)*.

The Crucible Group. 1994. *People, Plants and Patents. The Impact of Intellectual Property on Trade, Plant Biodiversity and Rural Society*. IDRC, Montreal, Canada.

Thies, E. 2000. *Incentive Measures Appropriate to Enhance the Conservatioin and Sustainable Use of Agrobiodiversity.* Deutsche Gesellschaft Technische Zusammenarbeit (GTZ). Eschborn, Germany. http://69.90.183.227/doc/case-studies/inc/cs-inc-gtz-incentivesagrobiodiv-workshop2009-en.pdf (*accessed* 16 May 2010).

Thijssen, M. H., Bishaw, Z., Beshir, A., and de Boef, W. (Eds.). 2008. *Farmer's Varieties and Seeds. Supporting Informal Sseed Supply in Ethiopia.* Wageningen International, Wageningen, The Netherlands.

Thinlay, X. 1998. *Rice Blast, Caused by Magnaporthe Grisea, in Bhutan and Development of Strategies for Resistance Breeding and Management.* Dissertation Eth No. 127777, Swiss Federal Institute of Technology, Zurich, Switzerland.

Thinlay, X., Finckh, M. R., Bordeosc, A. C., and Zeigler, R.S. 2000. Effects and possible causes of an unprecedented rice blast epidemic on the traditional farming system of Bhutan. *Agric. Ecosyst. Environ.* **78:** 237–248.

Thurston, H. D., Salick, J., Smith, M. E., Trutmann, P., Pham J. L., and McDowell, R. 1999. Traditional management of agrobiodiversity. **In:** *Agrobiodiversity. Characterization, Utilization and Management*. pp.211–243. Wood, D., and Lenné, J. M., Eds., CABI Publishing, Wallingford, UK.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. 2002. Agricultural sustainability and intensive production practices. *Nature* **418:** 671–677.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D., and Swackhamer, D. 2001. Forecasting agriculturally driven global environmental change. *Science* **292:** 281–284.

Toledo, A. 2002. Saving the seed - Europe's challenge. *Seedling*, April 2002, Grain Publications, Barcelona, Spain.

Triomphe, B., Sabourin, E., Hocde, H., Scopel, E., Oliveira de, M. N. de, Xavier J. H. V., Silva da, F. A., Macena da Silva, F. A., and Ramos de Almeida, S. C. 2008. Participatory cropping and farming system design among multiple stakeholders to contribute to sustainable agricultural production. Experiences and lessons with the agriarian reform sector in the Brazilian Cerrados. **In:** *Empowerment of the Rural Actors: A Renewal of Farming Systems Perspectives.* 8th European IFSA Symposium, Clermont-Ferrand, France, 6-10 July 2008. pp. 3–12. Dedieu, B., and Zasser-Bedoya, S., Eds., Clermont-Ferrand, France.

Tripp, R. 1998. Regulatory issues: varietal registration and seed quality control. **In:** *Maize Seed Industries in Developing Countries*. pp. 159–174. Morris M. L., Eds., Lynne Rienner Publishers and the International Maize and Wheat Improvement Center. Boulder, Colorado; London, UK; Mexico DF, Mexico.

Tripp, R. 2000. *GMOs and NGOs: Biotechnology, the Policy Process, and the Presentation of Evidence.* Overseas Development Institute (ODI), London, UK.

Tripp, R. 2001. *Seed Provision and Agricultural Development.* Overseas Development Institute (ODI), London, UK.

Tripp, R. 2002. Seed regulatory reform: an overview. *J. New Seeds***4:** 103–115.

Tripp, R. 2006. Strategies for seed system development in sub-Saharan Africa: a study of Kenya, Malawi, Zambia and Zimbabwe. *J. SAT Agric. Res.* **2**(1): 1–47.

Tripp, R. and Rohrbach, D. 2001. Policies for African seed enterprise development. *Food Policy* **26**(2): 147–161.

Trutmann, P., Fairhead, J., and Voss, J. 1993. Management of common bean diseases by farmers in the Central African highlands. *Int. J. Pest Manage.***39:** 334–342.

Trutmann, P., and Pyndji, M. M. 1994. Partial replacement of local common bean mixtures by high yielding angular leaf spot resistant varieties to conserve local genetic diversity while increasing yield. *Ann. App. Biol.* **125:** 45–52.

Trutmann, P., Voss, J., and Fairhead, J. 1996. Indigenous knowledge and farmer perception of common bean disease in the central African highlands. *Agric. Hum. Values* **13:** 64–70.

Tsehaye, Y., Berg, T., Tsegaye, B., and Tanto, T. 2006. Farmers' management of finger millet (*Eleusine coracana* L.) diversity in Tigray, Ethiopia, and implications for on-farm conservation. *Biodivers. Conserv.* **15**(13): 4289–4308.

Turgunbaev, K. T. 2009. Vinigradarstvo Kyrgyzstana. (Viticulture in Kyrgyzstan) *Vestnik of Kyrgyz Technical University*, Bishkek, Kyrgyzstan (in Russian).

Tushemereirwe, W. K. 1996. *Factors Influencing the Expression of Leaf Spot Diseases of Highland Bananas in Uganda*. PhD thesis, University of Reading, UK.

Tuxill, J., Reyes, L. A., Latournerie, L., Cob, V., and Jarvis, D. I. 2009. All maize is not equal: maize variety choices and mayan foodways in rural Yucatan, Mexico. **In***: Pre-Columbian Foodways: Interdisciplinary Approaches to Food, Culture and Markets in Mesoamerica.* pp. 467–486. Edited by Staller, J. E. and Carrasco, M. D., Eds., Springer, NY, USA.

UNORCAC 2008. *Unión de Organizaciones Campesinas e Indígenas de Cotacachi - Ecuador.* http://www.equatorinitiative.org/index.php?option

=com_content&view=article&id=543%3Aunorcac&catid=107%3Aequator-prize-winners-2008&Itemid=541&lang=en Accessed on 16 May 2010.

Valdivia, R. F. 2005. The use and distribution of seeds in areas of traditional agriculture.**In:** *Seed Systems and Crop Genetic Diversity On-Farm.* Proceedings of a workshop, September 16–20, 2003, Pucallpa, Peru. pp. 17–21. Jarvis, D. I., Sevilla-Panizo, R., Chavez-Servia, J. L. and Hodgkin, T., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Valdivia Bernal, R., Caro Velarde, F. de J., Ortiz Catón, M., Betancourt Vallejo, A., Ortega Corona, A., Vidal Martínez, V. A., and Espinosa Calderón, A. 2007. Participatory development of maize synthetic hybrids and seed production by farmers. *Agric. Técn. Méx.* **33**(2): 135–143.

Vallavieille-Pope de, C. 2004. Management of disease resistance diversity of cultivars of a species in single fields: controlling epidemics. *Comp. Rendus Biol.***327:** 611–620.

Van der Berg, H., and Jiggins, J. 2007. Investing in farmers- the impacts of farmers field schooling relation to integrated pest management. *World Dev.* **35**(4): 663–686.

Van der Steeg, R. P., Remington, T., Grum, M., and Kemigisha, E. 2004. Seed vouchers and fairs and agrobiodiversity in Western Uganda. **In:** *Addressing Seed Security in Disaster Response Linking Relief with Development.* pp. 29–43. Sperling, L., Remington, T., Haugen, J. M., and Nagoda, S., Eds. CIAT, Cali, Colombia.

Vandermeer, J. 1995. The ecological basis of alternative agriculture. *Ann. Rev. Ecol. and Syst.* **26:** 201–224.

Van Dusen, M. E. 2006. Missing markets, migration, and corp biodiversity in the *Milpa* system of Mexico: a household farm model. **In:** *Valuing Crop Biodiversity: On-farm Genetic Resources and Economic Change.* pp. 63–77. Smale, M., Eds., CABI Publishing, Wallingford, UK.

Van Dusen, M. E., Dennis, E, Ilyasov, J., Lee, M., Treshkin, S., and Smale, M. 2006. Social institutions and seed systems: The diversity of fruits and nuts in Uzbekistan. **In:** *Valuing Crop Biodiversity: On-farm Genetic Resources and Economic Change.* pp. 192–210. Smale, M., Eds., CABI Publishing, Wallingford, UK.

Van Dusen, E., Gauchanm, D., and Smale, M. 2007. On-farm conservation of rice biodiversity in Nepal: a simultaneous estimation approach. *J. Agric. Econ.* **58**(2): 242–259.

Van Dusen, M. E., and Taylor, J. E. 2005. Missing markets and crop diversity: evidence form Mexico. *Environ. Dev. Econ.* **10:** 513–531.

Van Noordwijk, M. 2005. *Rupes Typology of Environmental Service Worthy or Reward.* World Agroforestry Centre (ICRAF), Bogor, Indonesia. http://www.worldagroforestry.org:8090/water/downloads/Watershed%20Publications/2005%20van%20noordwijk.pdf

Vernooy, R., and Fajber, L. 2004. Making gender and social analysis work for natural resource management research: an umbrella program for building researcher capacity. **In:** *InterAction's Commission on the Advancement of Women and International Institute of Rural Reconstruction Gender Mainstreaming in Action: Successful Innovations from Asia and the Pacific*. pp. 208–223. Washington: InterAction's Commission on the Advancement of Women and Silang, Cavite: International Institute of Rural Reconstruction, Wa DC., USA.

Visser, B., and Jarvis, D. I. 2000. Upscaling approaches to support on-farm conservation. Encouraging biodiversity-the conservation and development of plant genetic resources. **In:** *Proceedings of the Baarlo Workshop*. pp. 134–141. Almekinders, C. and De Boef, W., Eds., Intermediate Technology Publications, London, UK.

Voss, J. 1992. Conserving and increasing on-farm genetic diversity: farmer management of varietal bean mixtures in central Africa. **In:** *Diversity, Farmer Knowledge and Sustainability*. pp. 34–51. Moock, J.L. and Rhoades, R.E., Eds., Cornell University Press, Ithaca, NY, USA.

Waage, J. K., Mumford, J. D., Pollock, C., Pretty, J., Crute, I., Leaver, C. and Dalton, H. 2008. Agricultural biosecurity. *Phil. Trans. R. Soc. B.* **363**(1492): 863–876.

Wale, E. In press. On biodiversity impact assessment: the rationale, conceptual challenges and implications for future EIA. **In:** *Examining the Impact of Development Interventions on Biodiversity: Lessons from GRPI-Egypt*. Halewood, M. and Wale, E., Eds. Genetic Resources Policy Initiative, Bioversity International. Rome, Italy.

Wale, E., Chishakwe, N., and Lewis-Lettington, R. 2008. Cultivating participatory policy processes for genetic resources policy: lessons from the Genetic Resources Policy Initiative (GRPI) project. *Biodivers.Conserv.* **18:**1–18.

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G. D., and Pritchard, R. 2002. Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Conserv. Ecol.* **6**(1): 14. [online] URL: http://www.consecol.org/vol6/iss1/art14 (accessd 9 May 2010)

Walker, B., Sayer, J., Andrew, N. L., and Campbell, B. 2010. Should enhanced resilience be an objective of natural resource management research for developing countries? *Crop Sci.* **50:** 10–19.

Walsh, S., Bihizi, J. M., Droeven C., Ngendahayo, B., Ndaboroheye, B., and Sperling, L. 2004. Drought, civil strife, and seed vouchers and fairs: the role of the trader in the local seed system. **In:** *Addressing Seed Security in Disaster Response: Linking Relief with Development.* pp. 15–28. Sperling, L., Remington, T., Haugen, J. M., and Nagoda S., Eds., International Center for Tropical Agriculture, Cali, Colombia.

Wambugu, P. W., Mathenge, P. W., Auma, E. O., and van Rheenen, H. A. 2009. Efficacy of traditional maize (*Zea mays* L.,) seed storage methods in Western Kenya. *Afr. J. Food Agric. Nutr. Dev.* **9**(4): 1110–1128. http://www.ajfand.net/Issue25/PDFs/Wambugu8010.pdf

Wang, J., and Caballero, A. 1999. Developments in predicting the effective size of subdivided populations. *Heredity* **82:** 212–226.

Wilson, C., and Tisdell, C. 2001. Why farmers continue to use pesticides despite environmental, health and sustainability costs. *Ecol. Econ.* **39**(3): 449–462.

Weltzien, E., Rattunde, H. F. W., Clerget, B., Siart, S., Toure, A. and Sagnard, F. 2006. Sorghum diversity and adaptation to drought in West Africa. **In:** *Enhancing the Use of Crop Genetic Diversity to Manage Abiotic Sress in Agricultural Production Systems. 23-27 May, Budapest, Hungary.* pp. 31–38. Jarvis, D., Mar, I. and Sears, L., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Weltzien, E., and vom Brocke, K. 2000. Seed systems and their potential for innovation: conceptual framework for analysis.**In:** *Targeting Seed Aid and Seed System, Interventions: Strengthening Small Farmer Seed Systems in East and Central Africa.* pp. 9–13. Proceedings of a workshop, June 21–24, 2000, Kampala, Uganda. Kampala*: CIAT.* Sperling, L., Eds., Cali, Colombia.

Whitlock, M. C. 2003. Fixation probabilities and time in subdivided populations. *Genetics* **164:** 767–779.

Williams, K. A. 2009. Conserving crop diversity and a way of life in Ecuador. *Agric. Res.* **57**(7): 10–11.

Williams, D., and Ramirez, M. 2006. Native crop demonstration gardens. Plant conservation in a changing world. Botanic gardens take lead in climate change talks. *Bot. Garden Conserv. Int. Quarterly Newsl. (Cuttings)***3:** 5.

Witcombe, J. R., Gyawali, S., Sunwar, S., Sthapit, B. R., and Joshi, K. D. 2006. Participatory plant breeding is better described as highly client-oriented breeding II. Optional farmer collaboration in the segregating generations. *Expl. Agric*. **42:** 79–90.

Witcombe, J. R, Hollington, P. A., Howarth, C. J., Reader, S., and Steele, K. A. 2008. Breeding for abiotic stresses for sustainable agriculture. *Phil. Trans. R. Soc. B* **363:** 703–716.

Witcombe, J. R., Joshi, K. D., Gyawali, S., Musa, A. M., Johansen, C., Virk, D. S., and Sthapit, B. R. 2005. Participatory plant breeding is better described as highly client oriented plant breeding. I. Four indicators of client orientation in plant breeding. *Exp. Agric.* **41** (3): 299–319.

Witcombe, J. R., Joshi, A., Joshi, K. D., and Sthapit, B.R. 1996. Farmer participatory crop improvement. I. Varietal selection and breeding methods and their impact on biodiversity. *Expl. Agric.* **32:** 445–460.

Worede, M. 1997. Ethiopian *in situ* conservation. **In:** *Plant Genetic Conservation: The In situ Approach.* pp. 290–301. Maxted, N., Ford-Lloyd, B. V., and Hawkes, G., Eds., Chapman and Hall Ltd. London, UK.

Worede, M., Teshome, A., and Tesemma, T. 2000. Participatory approached linking farmer access to genebanks: Ethiopia. **In:** *Participatory Approaches to the*

Conservation and Use of Plant Genetic Resources. pp. 56–61. Friis-Hansen, E., and Sthapit, B., Eds., International Plant Genetic Resources Institute, Rome, Italy.

Wunder, S., Engel, S., and Pagiola, S. 2008. Taking stock: a comparative analysis of payments for environmental services programs in developed and developing countries. *Ecol. Econ.* **65:** 834–852.

Yue, B., Xue, W., Xiong, L., Yu, X., Luo, L., Cui, K., Jin, D., Xing, Y., and Zhang, Q. 2006. Genetic basis of drought resistance at reproductive stage in rice: separation of drought tolerance from drought avoidance. *Genetics* **172:** 1213–1228.

Yupit-Moo, E. 2002. *Seed Storage Systems of Milpa Crops in Yaxcaba, Yucatan*. Unpublished BS thesis, Instituto Tecnologico Agropecuario No. 2, Yucatán, Mexico.

Zannou, A. 2009. Economic assessment of seed-tuber practices of yam *Dioscorea cayenensis* and *Dioscorea rotundata* planting materials. *Afr. J. Agric. Res.* **4**(3): 200–207.

Zhu, Y., Chen, H., Fan, J., Wang, Y., Li, Y., Chen, J., Fan, J. X., Yang, S., Hu, L., Leung, H., Mew, T. W., Teng, P. S., Wang, Z., and Mundt, C. C. 2000. Genetic diversity and disease control in rice. *Nature* **406:** 718–722.

Zimmerer, K. S. 1996. *Changing Fortunes: Biodiversity and Peasant Livelihood in the Peruvian Andes*. University of California Press, Los Angeles, California, USA.

Zimmerer, K. S. 2003. Just small potatoes (and ulluco)? The use of seed-size variation in “native commercialized” agriculture and agrobiodiversity conservation among Peruvian farmers. *Agric. Hum. Values* **20:** 107–123.

Critical Reviews in Plant Sciences, 30:177–197, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554417

Agroecosystem Management and Nutritional Quality of Plant Foods: The Case of Organic Fruits and Vegetables

K. Brandt,[1] C. Leifert,[2] R. Sanderson,[3] and C. J. Seal[1]
[1]*School of Agriculture, Food and Rural Development, Human Nutrition Research Centre, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom*
[2]*Nafferton Ecological Farming Group, Newcastle University, Stocksfield, NE43 7XD, United Kingdom*
[3]*School of Biology, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom*

Table of Contents

Organic and conventional crop management systems differ in terms of the fertilisers and plant protection methods used. Ecological and agronomic research on the effect of fertilization on plant composition shows that increasing availability of plant available nitrogen reduces the accumulation of defense-related secondary metabolites and vitamin C, while the contents of secondary metabolites such as carotenes that are not involved in defense against diseases and pests may increase. In relation to human health, increased intake of fruits and vegetables is linked to reduced risk

---

Address correspondence to R. Brandt, School of Agriculture, Food and Rural Development, Human Nutrition Research Centre, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom. E-mail: kirsten.brandt@ncl.ac.uk

Referee: Prof. Denis Lairon, INRA, UMR 1260, Nutriments Lipidiques et Prévention des Maladies Métaboliques, U476, Univ. Aix-Marseille, Faculté de Médecine, 13385 Marseille, France.

of cancer and cardiovascular disease. This benefit may be primarily due to their content of defense-related secondary metabolites, since most other constituents of fruits and vegetables either are not unique to these foods or have been shown to not provide health benefits when the intake is increased. A meta-analysis of the published comparisons of the content of secondary metabolites and vitamins in organically and conventionally produced fruits and vegetables showed that in organic produce the content of secondary metabolites is 12% higher than in corresponding conventional samples ($P < 0.0001$). This overall difference spans a large variation among sub-groups of secondary metabolites, from a 16% higher content for defence-related compounds ($P < 0.0001$) to a nonsignificant 2% lower content for carotenoids, while vitamin C showed a 6% higher content ($P = 0.006$). Based on the assumption that increasing the content of biologically active compounds in fruits and vegetables by 12% would be equivalent to increasing the intake of fruits and vegetables by the same 12%, a model developed to calculate the health outcome of increasing the intake of fruits and vegetables was then used to tentatively estimate the potential increase in life expectancy that would be achieved by switching from conventional to organic produce without changing the amount consumed per day, to 17 days for women and 25 days for men.

Keywords Organic food, secondary metabolites, plant defense compounds, health benefits, meta-analysis

I. INTRODUCTION

Consumers buy organic food for a variety of reasons, one of them being an interest to promote their own health (Schifferstein and Ophuis, 1998; Bourn and Prescott, 2002; Magkos *et al.*, 2003; Ekelund and Tjarnemo, 2004; Yiridoe *et al.*, 2005; Dangour *et al.*, 2009). The present paper reviews and analyses the present state of knowledge regarding how organic farming methods affect the content of secondary metabolites and vitamins in fruits and vegetables compared with the methods used in conventional agriculture, and how this may affect the health of consumers, in particular as regards the risk of cancer and cardiovascular disease.

A. Definition of Organic and Conventional Farming in the Present Context

The basic principles of organic agriculture are ‘health, ecology, fairness, and care’ (IFOAM, 2005). In many countries the procedures and inputs allowed in agriculture to produce foods labelled as organic are defined by law, including since 1991 the EU (Council Regulation (EC) No. 834/2007 (succeeding Council Regulation (EEC) 2092/91) (European Commission, 2007)), and since 2002 the USA (The National Organic Program (NOP)(USDA, 2009)). Regarding fruits and vegetables, the legal standards ban or limit the use of synthetic pesticides, fertilisers and other nonorganic inputs and define maximum allowed use of organic fertilizer, and if products are offered for sale to the public, the producer must be certified by an approved certifying body. Within organic agriculture each organisztion may then define standards for its members that go further than the legal requirements. For example, some producers adhere to biodynamic principles, which aim to ‘revitalise nature, grow nourishing food and advance the physical and spiritual health of humanity’ (Biodynamic Agricultural Association, 2009).

For nonorganic agriculture, Integrated Pest Management (IPM), Integrated Crop Management (ICM) and similar regulated systems define their aims as to “coordinate the use of pest biology, environmental information, and available technology to prevent unacceptable levels of pest damage by the most economical means, while posing the least possible risk to people, property, resources, and the environment” (Anonymous, 2004), while, by default, conventional agriculture aims to maximize the return on investment within the conditions set by environment protection legislation and customer specifications. Often these goals are not mutually exclusive, so while the minimum standards for each system are similar across the world, the differences in actual practices between production systems can vary substantially in different regions. In Europe and the United States, most fruits and vegetables are produced using IPM/ICM systems, operated by supermarket chains, producer cooperatives or other organisations [e.g., Assured Produce (2008), EUREPGAP (2004)].

II. EFFECT OF PRODUCTION METHOD ON COMPOSITION OF PLANT PRODUCTS

The composition of a fruit or vegetable is known to depend on a wide range of genetic and environmental factors, many of which, such as climate, ozone pollution and maturity at harvest, are independent of the production system (Gobbo-Neto and Lopes, 2007). Only factors that differ systematically between organic and conventional farming have the potential to cause a systematic difference in product composition. Such factors must depend directly or indirectly on aspects that are universally specified in the rules and regulations defining organic farming. The two groups of basic aspects that differ systematically between organic and conventional farming systems are: 1. restrictions on the use of synthetic pesticides, and 2. restrictions on the type and intensity of fertilization.

Restrictions on pesticides has the direct effect of reducing the content in organic products of residues of pesticides that are allowed in conventional farming (Lairon, 2010). Those same restrictions also indirectly affect variety choices, since organic farmers will put more emphasis on genetic resistance when choosing plant varieties than corresponding conventional farmers. Highly resistant varieties tend to have relatively high contents of defense-related secondary metabolites (Sanford *et al.*, 1992; Leiss *et al.*, 2009), so if they are overrepresented among the organic produce on the market, as indicated by some studies on apples (Veberic *et al.*, 2005), it might affect the overall plant food composition. This hypothesis would be relatively easy to test, however, the authors are not aware of any research surveys or other studies that have addressed it directly.

Restrictions on fertilizers directly result in a lower nitrogen content in organic plant products compared with corresponding conventional ones. In some cases, most commonly in cereals, the nitrogen content is presented as 'protein,' based on the assumption that the protein content is directly proportional to the nitrogen content. This is however not always the case, particularly not in vegetables where a proportion of the nitrogen occurs as nitrate. However, the difference in availability of plant available nitrogen also has a range of indirect effects, due to the effect of nitrogen on plant metabolism and physiology, which systematically affect the contents of some vitamins and plant secondary metabolites, as detailed in the following section.

A. Ecological Background for Differences in Composition

Extensive studies, reviewed e.g., by Koricheva *et al.* (1998) and Stamp (2003), have explored how nutrient availability affects secondary metabolism of plants in the context of ecology, the science of the relationships between organisms and their environments. Increased fertilisation with nitrogen (under nitrogen-limited conditions) causes a reduction in the content of phenolic compounds in the leaves, and this reduction has been shown to match models of trade-off between growth and defence (under conditions where no pesticides are used). Under the conditions prevailing in most natural environments, when plants gain access to an increased supply of nutrients, the optimal improvement in fitness is achieved by using these additional resources for increasing the growth rate, rather than for accumulation of phenolic defense compounds (de Jong, 1995).

B. Effects of Fertiliser Dose on Contents of Secondary Metabolites and Vitamins

Experiments with crops exposed to different intensities of fertilization have shown similar effects as in natural environments (Norbaek *et al.*, 2003; Gayler *et al.*, 2004; Toor *et al.*, 2006; Palit *et al.*, 2008; Sousa *et al.*, 2008; Flores *et al.*, 2009a). Recently, a different line of research has developed 'a systemic approach monitoring the response of plants to withdrawal and/or re-supply of mineral nutrients at the level of transcripts, metabolites and enzyme activities' (Fritz *et al.*, 2006; Amtmann and Armengaud, 2009). The results, that removal of N-fertilizer increases the content of phenylpropanoid defencs compounds, but not carotenes, are broadly in line with the plant-level experiments, confirming that they reflect common or even universal patterns of metabolic regulation, probably evolved to provide optimal responses to natural fluctuations in nutrient availability.

Both approaches indicate that in an agricultural context a decrease in nitrogen availability to the plants will result in increased content of phenolic defense compounds, which then increases the resistance of the plants to pests and diseases, although at the cost of a lower growth rate and therefore in a lower yield (Brandt and Molgaard, 2001).

Some authors have also suggested that the absence of protection from pesticides would result in initially higher rates of attack by pests and pathogens in organic plants compared with corresponding conventional ones, triggering the formation of induced defense compounds, which then subsequently protect the plant against diseases or pests (Bourn and Prescott, 2002; Young *et al.*, 2005). However, studies into the protein expression profiles of potatoes grown in a factorial long-term experiment set up as part of the Quality Low Input Food project (FP6-FOOD-CT-2003-506358) showed that differences in the tuber composition were mainly linked to differences in fertilisztion rather than crop protection regimes between organic and conventional systems (Lehesranta *et al.*, 2007). Approximately 14% of proteins were differentially expressed when potatoes grown under conventional mineral fertilization were compared with potatoes fertilized with composted manure-based organic fertilization regimes in this study. Also in another study where the hypothesis was tested experimentally, by using factorial combinations of organic and conventional fertilizers and pesticide regimes under greenhouse conditions with low pest load, all the differences in content of secondary metabolites were due to the fertiliser treatments, with no effect of the pesticide treatments (Zhao *et al.*, 2009).

In the context of conventional agriculture, studies of fertilization doses have rarely included measurements of the contents of secondary metabolites, since most studies of plant composition have focused on nutrients. However Gayler *et al.* (2004) found similar effects as in the ecological studies performed in natural rather than agricultural environments. In contrast many studies show that increased fertilization tends to reduce the contents of ascorbic acid (vitamin C), as reviewed by Lee and Kader (2000) as well as increase the content of beta-carotene (which can be converted into vitamin A) (Mozafar, 1993). For secondary metabolites that are neither nutrients nor defence related, such as colorants or (some) volatiles, only few data on the effect of fertilisation are available, and no clear pattern is described.

Given that yields in organic systems are usually significantly lower than in conventional production, it appears that the yield reduction and changes in composition caused by the restrictions in fertilizer use are directly linked. If so, future improvements in organic production methods (e.g., improved fertilization regimes), which would allow farmers to achieve higher growth rates (yields), may also result in more similar product compositions between organic and conventional products, as suggested by Brandt and Mølgaard (2001) and Benbrook (2007). However, the temporal nutrient release patterns from mineral fertilizers differ significantly from those of organic fertilizers, mainly because macro- and micro-nutrients in organic fertilizzers only become plant available after mineralization by the soil biota (Lambers *et al.*, 2009). Contrasting relative availability pattern throughout the growing season may therefore result in differences in composition even at similar yield levels.

III. PLANT FOODS AND CONSUMER HEALTH

A. Research on Organic Foods in Relation to Consumer Health

The studies comparing nutrient content of organic and conventional foods have been extensively reviewed (e.g, Woese *et al.*, 1997; Heaton, 2001; Worthington, 2001; Bourn and

Prescott, 2002; Gennaro and Quaglia, 2002; Williams, 2002; Magkos *et al*., 2003; Winter and Davis, 2006; Rembialkowska, 2007; Benbrook *et al*., 2008; Dangour *et al*., 2009; Lairon, 2010).

While most of these reviews described systematic differences in composition, only very few of them attempted any assessment of the relevance of these differences for population health. Compared with conventional high-input production, in cases where there are differences in composition, organic plant foods tend to show higher levels of vitamin C, less nitrate, less total protein, higher levels of plant secondary metabolites (phytochemicals), lower contamination with mycotoxins and pesticide residues and a higher proportion of essential amino acids in the protein. However, it is also emphasized in most reviews that for any one nutrient most studies show no significant differences, and that these differences are not sufficiently consistent to predict the content in a food, based on knowledge about its production system.

Another general observation emphasised in most of the reviews is that many other factors affect the concentrations of all these nutrients, and often by much more than the production system. For example, for most compounds studied the variation from year to year or from variety to variety has much greater effect on the content than whether the plant is grown in an organic or conventional production system. Depending on the context of the review, and on whether it addresses the interests of the individual consumer ('value for money') or the nutritional status of a population, but seemingly irrespective of whether the review was purely qualitative (Woese *et al*., 1997; Bourn and Prescott, 2002; Gennaro and Quaglia, 2002; Williams, 2002; Magkos *et al*., 2003; Winter and Davis, 2006; Lairon, 2010) or included a more or less systematic quantitative element (Heaton, 2001; Worthington, 2001; Rembialkowska, 2007; Benbrook *et al*., 2008; Dangour *et al*., 2009) the range of interpretations of the limited experimental data is remarkably wide, from 'crops are significantly different' (Heaton, 2001) to 'no evidence for a difference' (Dangour *et al*., 2009). In most cases the authors of the reviews then conclude that more studies are needed before it is possible to make any firm conclusions about the potential consequences of any differences for human health.

B. Effects on Health of Fruits and Vegetables and Their Constituents

In developed countries such as the UK, the majority of the population obtain sufficient or more than sufficient amounts of vitamin C, minerals and protein, and if any widespread deficiencies are identified, fortification programs are established to alleviate them (Hoare *et al*., 2004). Of the few people who are deficient in nutrients that are present in substantial amounts in vegetables and fruit, most eat next to nothing of these foods, so these population segments would not benefit from increased concentrations of these nutrients in the produce. The intake survey data are supported by intervention studies with vitamin C and other vitamins and carotenoids common in plants, which show either no effect or an increase in the risk of diseases such as cancer (Gaziano *et al*., 2009; Lin *et al*., 2009) or cardiovascular disease (Bjelakovic *et al*., 2008).

Still, many studies show negative associations between the intake of fruits and/or vegetables and the risk of cancer (Linseisen *et al*., 2007; Murthy *et al*., 2009) or cardiovascular disease (Dauchet *et al*., 2009), indicating a preventive role of these foods that cannot be explained merely by the supply of vitamins. Such studies form the basis for methods developed to estimate the effect on public health of factors that change the intake of fruits and vegetables (Veerman *et al*., 2006).

In contrast, in low-income populations, mainly in developing countries, vegetables and fruits are important sources of essential vitamins, minerals, and high-quality proteins in short supply in the population's diet, so for them the content of nutrients in vegetables and fruits are important for health (Ali and Tsou, 1997). Vitamin C and vitamin A deficiency are common in some developing countries, and here an increase in concentrations would be beneficial for health. However, we found no studies that compared the vitamin C or beta-carotene contents in organically produced vegetables with the contents in vegetables from the low-input "subsistence" agriculture, which shows crop yields that are lower than on comparable organic farms (Badgley *et al*., 2007), and provides most of the vegetables and fruits that are available for the poorest populations. Due to this, the present review is only discussed in relation to the nutritional situation in more affluent populations, where most of the fruits and vegetables originate from commercial horticultural production.

C. Choice of Topics for More Detailed Analysis

The present review focuses on secondary metabolites and vitamins in fruits and vegetables including herbs. These two relatively well-defined (although partially overlapping) groups of compounds represent a large proportion of all the available data on compositional differences between organic and conventional foods, while for most other groups of compounds, only a few comparable studies are available for each. The secondary metabolites and vitamins are often considered the main beneficial components of vegetables and fruits (Brandt and Mølgaard, 2001; Brandt *et al*., 2004). To some extent this view is deduced by elimination, since for most other nutrients in plants, such as minerals and proteins, fruits and vegetables are not the main dietary sources and therefore they cannot be responsible for the above-mentioned health benefits of this food category. The two other groups of dietary constituents where fruits and vegetables are the primary dietary sources are pesticide residues and nitrate.

Regarding pesticide residues, despite well known harmful effects at elevated exposure levels (Brandt, 2007; Lairon, 2010) to the best of the authors' knowledge, no published studies have shown any unequivocal health benefits nor detrimental effects of the pesticides currently licensed in Europe at the levels normally found in fruits and vegetables, possibly because the benefits of consumption of these foods tend to outweigh potentially negative effects of the pesticide residues in them (Juhler *et al.*, 1999). So even for a very substantial relative difference in content, it would be difficult to estimate any consequences for consumer health.

Regarding nitrate, as mentioned above, the difference in content between organic and conventional produce can be seen as a direct consequence of the restrictions on fertilizer use in organic farming, and is mentioned in most reviews of the topic (Woese *et al.*, 1997; Bourn and Prescott, 2002; Williams, 2002; Magkos *et al.*, 2003; Winter and Davis, 2006). Several reviews have reported estimates of the difference in nitrate content between organic and conventional products: 16% with $P = 0.19$ (Dangour *et al.*, 2009); difference in 14 of 16 studies (Heaton, 2001); approximately 50% (Lairon, 2010); 49% (Rembialkowska, 2007), and 15.1% with $P < 0.0001$ (Worthington, 2001). However, while an increasing number of studies indicate that and how plant-derived nitrate may provide significant benefits for human health (McKnight *et al.*, 1999; Lundberg *et al.*, 2008), quantitative data on consequences for health of the consumer are scarce and controversial, and some data are being published in support of the view of nitrates as a health hazard, e.g., Winter *et al.* (2007), which forms the basis for the present restrictive standards (Santamaria, 2006). Due to this, while acknowledging that the difference in nitrate content exists and is likely to be important for health, the present review will not attempt to address the magnitude of the difference in nitrate content nor the potential impact on human health.

Regarding primary metabolites, such as sugars, simple organic acids, proteins, and minerals, there is very little if any information in the literature on what effect a (modest) difference in intake might have on health. For these compounds there is also no clearly defined background information that would allow predictions of how the differences between the production systems will affect the content in the plants, so it would not be possible to compare any effects on content with the biological mechanism or at least selection pressures involved. As for nitrate, this is something that it might be relevant to return to, once the relevant background knowledge linking intake and health outcomes has been established.

IV. META-ANALYSIS OF DIFFERENCES IN CONTENTS OF SECONDARY METABOLITES AND VITAMINS IN FRUITS AND VEGETABLES

To assess the (potential) effect on consumer health of differences in composition between organic and conventional plant foods, it is necessary to estimate the magnitude of this difference. This can be done using the method of meta-analysis, where data from different studies are combined to improve the ability to detect and quantify effects of systematic factors, irrespective of randomly occurring factors such as climate, soil type, or variety.

A. Methods

Papers were identified through an initial search of the literature using the search terms ‘(organic* or ecologic* or biodynamic*) and (conventional* or integrated) and (fruit* or vegetable* or strawberr* or apple* or spinach or carrot* or pea* or lettuce or currant* or cherr* or potato* or cabbage* or banana* or tomato*)’ with Web of Science, for the period January 1992 – October 2009. This provided 2,512 references, where titles and (if available) abstracts were checked, to extract 84 studies reporting original data of comparisons of vitamins or secondary metabolites of fruits, herbs, and vegetables grown using organic and conventional methods, as well as eight reviews of the topic. Further hand searches of reference lists of reviews and original papers provided 34 additional references. Of these 118 references, 11 were unavailable and five turned out to contain ‘duplicate’ data from the same experiment and year(s), leaving 102 separate relevant papers. In two cases sets of papers were partial duplicates, where one paper reported the first year of a trial and another paper the average of two or three years.

Each paper was graded for a range of criteria (Tables 1 and 2) to determine their relevance for the study. As recommended by Englund *et al.* (1999), the criteria for inclusion and exclusion were examined critically to avoid unnecessary loss of statistical power due to unconscious bias.

The retained criteria related to the experimental design rather than to the general scientific quality of the paper, although some papers of low general quality still had to be excluded because the method description was not sufficiently detailed to determine all critical aspects of the design. Specifically, conference proceedings and other non-reviewed publications were included with the same weight as articles in peer-reviewed journals, if the description of the experimental design was sufficiently clear and detailed to assess that the design was appropriate. The criteria for inclusion (Table 2) were as recommended by Harker (2004): appropriate experimental treatments; relevance of the organic/conventional practices used; that the same varieties were used in both systems; and that products from both production systems were grown in (approximately) the same location.

Regarding experimental treatments, the description had to be sufficiently detailed to allow assessment of the other criteria; the plant product should be a food or drink or raw material for such products, and if processed, the processing methods should not differ between organic and conventional samples; the sample size and sample preparation should meet minimum standards comparable to the requirements for publication in a low-impact journal, defined as that a sample should contain material from at least three separate plants or five randomly chosen fruits or vegetables, e.g., as a comparable amount of product by weight, and represent all of the edible part of the product (with or without edible peel/skin/pomace if relating to a product that does not necessarily contain these parts), and that the sample preparation should not include steps appearing to severely degrade the compound in question.

TABLE 1
Papers included in the analysis, which all met criteria for inclusion

Reference	Plant species	Number of replications or harvest dates	Number of varieties	Number of years	Type of study design	Documentation of organic treatment			Sub-type of conventional system	Notes
						Inputs listed in method description	Certification explicitly stated	In legally defined context		
(Abreu *et al*., 2007)	Potato	1	2	1	Un-replicated field trial	Yes	No	Yes	Conventional	Data from 'integrated' treatment not used
(Amodio *et al*., 2007)	Kiwi	1	1	1	On-farm field trial	Yes	Yes	Yes	Conventional	
(Anttonen and Karjalainen, 2006)	Black currant	3	1	1	On-farm field trial	Yes	Yes	Yes	Conventional	
(Anttonen *et al*., 2006)	Strawberry	2	6	1	On-farm field trial	Yes	Yes	Yes	Conventional	
(Asami *et al*., 2003)	Marionberry, Sweet corn	1	2	1	Farm pair	Yes	No	Yes	Conventional	Data from 'sustainable' treatment not used
(Barrett *et al*., 2007)	Tomato	4	1	1	On-farm field trial	Yes	No	Yes	Conventional	
(Beltran-Gonzalez *et al*., 2008)	Mandarin orange juice	1	1	1	Un-replicated field trial	Yes	No	Yes	Conventional	
(Camin *et al*., 2007)	Potato	1	1-2	3	Farm pairs	Yes	No	Yes	Integrated pest management	Four pairs in total
(Carbonaro and Mattera, 2001)	Pear, Peach	1	2	1	Un-replicated field trial	No	No	Yes	Conventional	Probably some overlap of data with Carbonara *et al*. 2002
(Carbonaro *et al*., 2002)	Pear, Peach	1	2	3	Un-replicated field trial	No	No	Yes	Conventional	Probably some overlap of data with Carbonara and Mattera 2002
(Caris-Veyrat *et al*., 2004)	Tomato	1	3	1	On-farm field trial	Yes	No	Yes	Integrated pest management	
(Cayuela *et al*., 1997)	Strawberry	1	1	1	On-farm field trial	Yes	No	Yes	Conventional	
(Chassy *et al*., 2006)	Bell pepper, Tomato	1	2	3	Un-replicated field trial	Yes	Yes	Yes	Conventional	
(Chinnici *et al*., 2004)	Apple	1	1	1	Farm pair	Yes	No	Yes	Integrated production	
(Dani *et al*., 2007)	Grape juice	1	1	1	Farm pair	No	No	Yes	Conventional	
(Fauriel, 2005; J. Fauriel, 2007)	Peach	4	1	2	Farm survey	No	Yes	Yes	Conventional	Data per year calculated from two papers
(Ferreres *et al*., 2005)	Cabbage	4	1	1	Un-replicated field trial	Yes	Yes	Yes	Conventional	Same plant material as Sousa *et al*. 2005
(Fjelkner-Modig *et al*., 2001)	Cabbage, Carrot, Onion, Pea, Potato	6	1	6	Replicated field trial	Yes	No	Yes	Integrated crop management	
(Forster *et al*., 2002)	Banana	11	1	1	Farm survey	No	No	Yes	Conventional	Same plant material as Mendes *et al*. 2003. Years not separated
(Hajslova *et al*., 2005)	Potato	2	8	4	Farm pairs/field trial	Yes	Yes	?	Good agricultural practice	Some data per year obtained from author

(Continued on next page)

TABLE 1
Papers included in the analysis, which all met criteria for inclusion *(Continued)*

						Documentation of organic treatment				
(Hakkinen and Torronen, 2000)	Strawberry	3	3	1	Farm pairs	No	No	Yes	Conventional	
(Hallmann, 2007)	Tomato	1	5	1	On-farm field trial	Yes	Yes	Yes	Conventional	
(Hamouz, 2005)	Potato	2	7	3	Replicated field trial	Yes	No	Yes	Conventional	
(Juroszek *et al*., 2009)	Tomato	3	2	2	Farm pairs	Yes	Yes	?	Conventional	Years not separated. Some overlap of data with Lumpkin 2005
(Kahu *et al*., 2009)	Black currant	4	3	3	Replicated field trial	Yes	No	Yes	Conventional	
(Keukeleire *et al*., 2007)	Hops	1	3	3	On-farm field trial	Yes	No	Yes	Conventional	
(Lamperi *et al*., 2008)	Apple	1.5	2	1	Farm pairs	No	No	Yes	Integrated crop management	
(Levite *et al*., 2000)	Wine	9	5	1	Farm pairs	No	No	Yes	Conventional	
(Lombardi-Boccia *et al*., 2004)	Plum	1	1	3	Un-replicated field trial	Yes (fertilisers)	No	Yes	Conventional	Years not separated
(Lumpkin, 2005)	Tomato	4	2	1	Farm pairs	Yes	Yes	?	Conventional	Some overlap of data with Juroszek *et al*. 2009
(Malusa *et al*., 2004)	Grape skin	1	1	1	Farm pair	Yes (fertilisers)	No	Yes	Conventional	
(Marin *et al*., 2008)	Sweet pepper	8*3	1	1	Farm pairs	Yes (fertilisers)	No	Yes	Integrated crop management	Data from ’soilless’ treatment not used. Years not separated
(Mendez *et al*., 2003)	Banana	11	1	1	Farm survey	No	No	Yes	Conventional	Same plant material as Forster *et al*. 2002. Years not separated
(Mikkonen *et al*., 2001)	Black currant	5	2	1	Farm survey	No	No	Yes	Conventional	
(Mitchell *et al*., 2007)	Tomato	3	1	10	Replicated field trial	Yes	No	Yes	Best management practice	
(Mogren *et al*., 2008)	Onion	4	1	1	Replicated field trial	Yes	No	Yes	Conventional	
(Moreira *et al*., 2003)	Swiss chard	1	1	1	Farm pair	No	Yes	?	Conventional	
(Mulero *et al*., 2009)	Red wine	9	1	1	Randomised field trial	Yes (pesticides)	No	Yes	Conventional	Experimental design is unclear, may be pseudo replications or farm pairs?
(Nobili *et al*., 2008)	Tomato	1	1	1	Farm pair	No	No	Yes	Conventional	
(Olsson *et al*., 2006)	Strawberry	1	2	1	Un-replicated field trial	Yes	No	Yes	Conventional	
(Ordonez-Santos *et al*., 2009)	Tomato	2	2	1	On-farm field trial	Yes	Yes	Yes	Controlled production	In the sense of complying with UNE 155102: 2005
(de Pascale *et al*., 2006)	Tomato	3	2	2	Replicated field trial	Yes	No	Yes	Conventional	
(Peck *et al*., 2006)	Apple	3	1	2	Replicated field trial	Yes	No	Yes	Conventional	Data from ’integrated’ treatment not used
(Perez-Lopez *et al*., 2007b)	Mandarin juice	1	1	1	Un-replicated field trial	Yes	Yes	Yes	Conventional	
(Pieper and Barrett, 2009)	Tomato	3	1	1	On-farm field trial	Yes	Yes	Yes	Conventional	

(Continued on next page)

TABLE 1
Papers included in the analysis, which all met criteria for inclusion *(Continued)*

Reference	Plant species	Number of replications or harvest dates	Number of varieties	Number of years	Type of study design	Documentation of organic treatment			Sub-type of conventional system	Notes
						Inputs listed in method description	Certification explicitly stated	In legally defined context		
(Rapisarda *et al*., 2005)	Orange (juice)	7	2	3	Farm pair survey	Yes	No	Yes	Integrated pest management	Years not separated
(Rembialkowska *et al*., 2007)	Apple puree	2*2	3	1	Farm pair survey	Yes	Yes	Yes	Conventional	
(Robbins *et al*., 2005)	Broccoli	1	1	1	On-farm field trial	No	Yes	Yes	Conventional	
(Rodriguez *et al*., 2006)	Tomato	1?*4	1	1	Farm pair survey	No	No	Yes	Conventional	
(Sousa *et al*., 2005)	Cabbage	1	1	1	Farm pair survey	Yes	No	Yes	Conventional	Same plant material as Ferreres *et al*. 2005. Order-of-magnitude error for vitamin C?
(Stracke *et al*., 2009b)	Apple	5	1	3	Farm pair trial	No	Yes	Yes	Integrated crop management	
(Tarozzi *et al*., 2004)	Apple	1	1	1	Farm pair survey	No	No	Yes	Integrated crop management	
(Tarozzi *et al*., 2006)	Red orange	4	1	1	Farm survey	No	Yes	Yes	Integrated crop management	Unclear description, maybe shopping basket?
(Valavanidis *et al*., 2009)	Apple	?	5	2	Farm pair survey	No	Yes	Yes	Conventional	Unclear no. of farm pairs. Years not separated
(Vian *et al*., 2006)	Grapes	1	1	1	Farm pair survey	Yes	No	Yes	Conventional	
(Wang *et al*., 2008)	Blueberry	5	1	1	Farm survey	Yes	Yes	Yes	Conventional	
(Warman and Havard, 1997)	Carrot, Cabbage	5	1	3	Replicated field trial	Yes	No	?	Conventional	
(Warman and Havard, 1998)	Potato, Sweet corn kernels	5	1	3	Replicated field trial	Yes	No	?	Conventional	
(Wszelaki *et al*., 2005)	Potato	1	1	1	Un-replicated field trial	Yes	Yes	Yes	Conventional	
(Young *et al*., 2005)	Lettuce, Collard green, Pak choi	?	1	1	Field trial	Yes	Yes	Yes	Conventional	Unclear as regards the number of replications.
(Zafrilla *et al*., 2003)	Wine	1	1	1	Farm pair survey	Yes (pesticides)	No	Yes	Conventional	
(Zhao *et al*., 2007)	Lettuce	6*2	2	1	Replicated field trial	Yes	No	Yes	Conventional	
(Zhao *et al*., 2009)	Pac choi	9*2	2	1	Replicated field trial	Yes	No	Yes	Conventional	

TABLE 2
Papers considered but not included in the analysis.

Reference	Type of study design	Plant species	Experimental design/quality	Organic/conventional	Same variety	Same growing conditions
(Baxter *et al*., 2001)	Shopping basket survey	Various spices etc. in soups	OK	OK	Not controlled	Not controlled
(Briviba *et al*., 2007)	Farm pair trial	Apples	Generally OK, but the data are a subset of the dataset in Stracke *et al*. 2009b, so this paper contains no unique data.	OK	OK	OK
(Chiesa *et al*., 2005)	Field trial	Tomato + 3 lettuce varieties	OK	One of 3 experiments had no organic treatment, and the other 2 had no relevant outcome data	OK	OK
(Daiss *et al*., 2008)	Replicated field trial	Swiss chard	OK	No conventional treatment	OK	OK
(Faller and Fialho, 2009)	Shopping basket survey	Carrot, Onion, Potato, Broccoli, White cabbage	OK	OK	Claimed, but not documented (no variety names)	Not controlled
(Flores *et al*., 2009a; Flores *et al*., 2009b)	Replicated field trial	Sweet pepper	OK	No organic treatment	OK	OK
(Grinder-Pedersen *et al*., 2003)	Shopping basket survey or farm trial depending on species	Several	OK	OK	No, only for some species, and their data not reported separately from the overall averages	Only partially controlled
(Hargreaves *et al*., 2008)	Replicated field trial	Raspberry	OK	No conventional treatment	OK	OK
(Hecke *et al*., 2006)	Farm trial or farm survey?	Apple juice	OK	OK	No	Not controlled
(Heimler *et al*., 2009)	Replicated field trial	Chicory	Single external leaves are not a generally consumed food product	OK	OK	OK
(Ismail and Fun, 2003)	Shopping basket survey	Five green vegetables	OK	OK	Not controlled	Not controlled
(Koh *et al*., 2008)	Shopping basket survey	Marinara sauce	OK	OK	Not controlled	Not controlled
(Kovacevic *et al*., 2008)	Farm survey	Strawberry	OK	Not enough information about organic inputs, certification and/or legal status to be completely certain of the definition	OK	Appears OK, but more detail would have been desirable
(Lima *et al*., 2008)	Farm survey	Peels or leaves of many species	Not generally consumed as foods	OK	Not controlled	Not controlled
(Lima *et al*., 2009)	Farm survey	Maize bran and tassels, Chinese cabbage leaves and stalks	Not generally consumed as foods	OK	OK for maize, not controlled for Chinese cabbage	OK

(Continued on next page)

TABLE 2

Papers considered but not included in the analysis *(Continued)*.

Reference	Type of study design	Plant species	Experimental design/quality	Organic/conventional	Same variety	Same growing conditions
(Masamba and Nguyen, 2008)	Shopping basket survey	Cabbage, carrot, Cos lettuce, Valencia orange	OK	OK	Possibly OK for orange, not controlled for the other species	Not controlled
(Matallana *et al*., 1998)	Shopping basket survey	Lettuce	OK	OK	Not controlled	Not controlled
(Meyer and Adam, 2008)	Shopping basket survey	Broccoli and red cabbage	OK	OK	Not controlled	Not controlled
(Palit *et al*., 2008)	Replicated field trial	Tea leaves	Several details missing, such as the season and developmental stage at sampling, selection of leaves for study	No description of plant protection, so not clear that there was any difference between treatments in this respect.	OK	OK
(Perez-Lopez *et al*., 2007a; Perez-Lopez *et al*., 2007c)	Un-replicated field trial	Sweet pepper	OK	Organic treatment unrealistic (too little fertiliser), despite complying with EC regulation	OK	OK
(Rembialkowska, 1999)	Farm pair survey	Potato	OK	OK	No, only for some samples, and their data not reported separately from the overall averages	OK
(Ren et al., 2001)	Farm trial	Many	Inadequate sample preparation: Vegetable juice polyphenols were allowed to polymerise for 20 minutes and the polymers removed, before polyphenols were measured	OK	OK	OK
(Riu-Aumatell *et al*., 2004)	Shopping basket survey	Pear, abricot and peach juices	OK	OK	Not controlled	Not controlled
(Rossi *et al*., 2008)	Un-replicated field trial	Tomato	Generally OK, but a key detail is missing from the published version of the paper	The organic plot was pre-treated with 100t ha^{-1} of sewage, contravening the EU regulation	OK	OK
(Schulzová and Hajšlová, 2007)	Field trial (not clear whether replicated or not)	Tomato	OK	No description of plant protection, so not clear that there was any difference between treatments in this respect.	OK	OK
(Sousa *et al*., 2008)	Field trial (not clear whether replicated or not)	Cabbage	OK	No description of plant protection, so not clear that there was any difference between treatments in this respect.	OK	OK

(Continued on next page)

TABLE 2

Papers considered but not included in the analysis *(Continued)*.

Reference	Type of study design	Plant species	Experimental design/quality	Organic/conventional	Same variety	Same growing conditions
(Stracke *et al*., 2009a)	Farm survey	Carrot	Generally OK, but outcome data only available in graphic format on logarithmic scale	OK	OK	OK
(Tinttunen and Lehtonen, 2001) 1	Shopping basket survey	Wine	Generally OK, but not controlled for differences in processing methods	OK	OK	Not controlled
(Toor *et al*., 2006)	Replicate field trial	Tomato	OK	No description of plant protection, so not clear that there was any difference between treatments in this respect. Also not clear which treatments are considered the 'standard' organic and 'standard' conventional, respectively	OK	OK
(Veberic *et al*., 2005)	Farm survey	Apple	OK	OK	No	Not controlled
(Versari *et al*., 2008)	Shopping basket survey	Abricot juice	OK	OK	Not controlled	Not controlled
(Weibel *et al*., 1998)	Farm trial	Apple	Generally OK, but non-significant comparisons not included	OK	OK	OK
(Wunderlich *et al*., 2008)	Shopping basket survey	Broccoli	OK	OK	Not controlled	Not controlled
(Yanez *et al*., 2007)	Shopping basket survey	Lemon juices	OK	OK	Not controlled	Not controlled
(Yanez *et al*., 2008)	Shopping basket survey	Fruit juices	OK	OK	Not controlled	Not controlled
(Yildirim *et al*., 2004)	Farm survey + processing trial	Wine	Generally OK, but not controlled for differences in processing methods	OK	OK	Not controlled

Regarding analytical methods, we did not require a detailed description, but we checked whether the values found were of the same order of magnitude as normally seen for the type of compound and species of plant, in particular for papers where methods were not described in detail. However, the only major deviation observed was in a paper with a detailed and appropriate method description (Sousa *et al*., 2005) (Table 1). These data were therefore retained in the analysis, since the out-of-range values were considered most likely to result from a simple scaling error that would affect all data within the study by the same incorrect factor, and therefore have no influence on the ratio of the values within the study.

Regarding relevance of the organic/conventional practices used, relevance of the organic was assessed by requiring at least one of three forms of documentation; 1. that input lists in the method description conformed to the requirements of Regulation (EC) No. 834/2007 or its predecessors; 2. that the growing location was certified; or 3. that the statement that a treatment was organic was made in a place (e.g., EU or USA) and time (>1992 or >2002, respectively) where it would be illegal to designate something as organic if it did not conform to the relevant regulations (Table 1).

Regarding relevance of the conventional treatment: where more than one form was included, only the data from 'conventional' treatments were used at the expense of 'integrated' or 'soilless,' based on the assumption that where these systems are the norm, they would not be contrasted with something else called 'conventional.' Where only one form of nonorganic treatment was used, this was considered the 'conventional,' unless indications were present that this was not the authors' intention. It is recognied that both organic and conventional crop management methods change considerably with time, so data from crops grown before 1992 were not included, to ensure that the results are relevant for the present situation.

For varieties, the variety name was required, since providing only the botanical cultivar classification such as 'white cabbage' or '*Brassica oleracea* cv *capitata,*' which may include any white cabbage varieties, was not considered sufficient to control this variable. Growing conditions were accepted as being the same if the paper included some statement indicating that provision of similar climate and soil type was taken into account in the selection of growing sites.

Among included papers, further quality criteria were defined (Table 1) relating to the number of replications and type of study, however these criteria were not used for weighting, and are presented here mainly to illustrate the wide range of designs among the studies, and the potential for future more detailed studies of the effect of study design on outcome. Generally, replicated field trials are considered the 'gold standard' for plant production experiments, because they allow full control of many of the confounding factors such as soil type and quality, plant genotype and (micro-) climate. However, they are costly and difficult to manage, in particular for treatments that must be established several years before a test can take place, as for comparisons of organic and conventional production systems. Even replicated field trials are susceptible to certain forms of inadvertent bias, for example if the crop does not mature at the same rate in each treatment or the trial's technical manager has less prior practical experience with one system than with the other, in particular if this manager does not have a background in commercial farming operations. Other options are farm trials and surveys, where farmers using already established different production systems grow a crop as part of their normal crop rotation. Here 'farm trials' are defined as studies where the investigator has influence on the crop and its cultivation, e.g., provides the seed and/or defines variables such as sowing dates, while 'farm surveys' rely on the purchase of material resulting from the normal activity of the farm. Farm trials and surveys can be paired (comparing farms or fields located near or even adjacent to each other to minimise differences in soil type and climate) as well as replicated, and well-designed farm-based studies can therefore in some cases provide more accurate estimates of the effects of commercially relevant production systems than field trials, despite less precision due to greater effect of random differences between experimental units. Surveys may also be conducted at the retail stage ('shopping basket surveys'), but while for some crops it would hypothetically be possible to purchase organic and conventional material of the same variety and produced in the same general area, in the present study no publications of shopping basket surveys were identified that met these criteria (Tables 1 and 2).

Based on best practice in meta-analyses of ecological experiments (Osenberg *et al.*, 1999), studies carried out in different years/growing seasons were considered independent, while replications of variety, place/farm pair and harvest time were considered not independent. So for each study, where possible, data were presented as averages of all comparable data within a species, compound and year/growing season. When data were reported as averages of several years, an attempt was made to obtain the data per year/season from the authors. Data from noncomparable samples were excluded from the calculation of averages, for example for a variety found only in one production system but not in the other. For post-harvest treatments, only data from the most freshly harvested treatment was used, partly because the present review focuses on the effect of the production phase, and partly since post-harvest concentration changes often are nonlinear and it therefore would be difficult to devise a consistent method for calculation of a meaningful average value across several durations of post-harvest storage.

Within a study and year/growing season, the data for each reported secondary metabolite or vitamin were recorded on fresh weight basis if reported (or possible to calculate), otherwise on dry matter basis. Regarding the number of different compounds measured within a class, it was observed, as noticed before (Benbrook *et al*., 2008), that this differed substantially among the publications, in particular in terms of detail, in the sense that some studies would report a wide range of different compounds

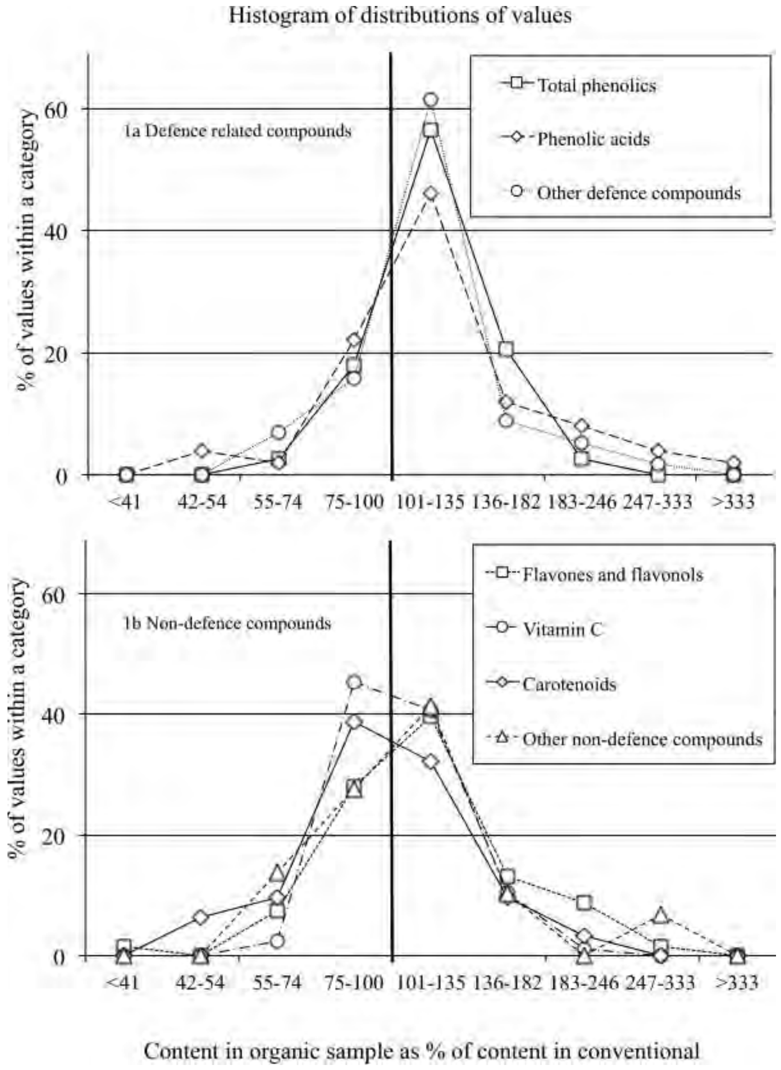

FIG. 1. Graphical representation of the distribution of ratios of content in organic and conventional fruits and vegetables, for different categories of compounds. The vertical line indicates 100% (where the concentrations are equal).

within a class of compounds, while others would report only the total of all compounds measured within a class. This may reflect efforts by authors to analyse as many compounds as possible in order to try to find a significant difference, and therefore poses a potential risk of inflating the effect size. The method chosen to (at least partially) alleviate this issue was that if the paper reported more than six different secondary metabolites, the contents of the members of groups of compounds were added up to fewer figures according to the following criteria (listed in order of priority): 1. Closely related structures such as isomers of the same compound; 2. Glucosides of the same aglycon; 3. Compounds of the same compound class present at similar levels. In this way each study could provide a maximum of six data pairs (organic compared with conventional) per plant species and year/growing season. Where available, data on dry matter content were also collected for each year/growing season and plant species. Data presented only in graphical form were read off the graphs by hand (after appropriate enlargement) using a ruler, except for one dataset (Stracke *et al*., 2009a) where this was not practically feasible because the graph was shown only on a logarithmic scale.

Each pair of values was used to calculate the ratio, as the content in the organic sample in % of the content in the conventional sample. The compounds were grouped into seven groups according to a combination of chemical structure and their function in the plant: 1. Total phenolics (as measured using the Folin-Ciocalteu method); 2. Phenolic acids; 3. Other defense compounds (tannins, alkaloids, chalcones, stilbenes, flavanones and flavanols, hop acids, coumarins and aurones); 4. Carotenoids; 5. Flavones and flavonols; 6. Other non-defense compounds (comprising mainly anthocyanins and volatiles); and 7. Vitamin C. The values used were as reported in the study, or calculated

TABLE 3

Results of meta-analysis of fruit and vegetable constituents.

Functions	Defense secondary metabolites	All defence	Non-defense secondary metabolites			All non-defence	All secondary metabolites	Anti-oxidant		
Types of compounds	Total pheno-lics	Phenolic acids	Other defense com-pounds [a]	Sum or average of 3 groups	Caro-tenes	Flavones and flavonols	Other non-defense compounds [b]	Sum or average of 3 groups	Sum or average of 6 groups	Vitamin C
N[c]	39	50	57	146	32	68	29	129	275	86
Of which on dry matter basis	9	13	15	37	0	20	6	26	63	3
Back-transformed ln(ratio)[d] (%)	114	120	113	116	98	111	108	107	112	106
P from re-sampling test	0.0002	0.0004	0.0007	<0.0001	0.634	0.0076	0.114	0.0104	<0.0001	0.0055
P from t-test	0.001	0.002	0.002	0.000	0.731	0.016	0.222	0.021	0.000	0.014
Standard error of the mean	4	6	4	3	6	4	7	3	2	2
Back-transformed ln(ratio)s without dry matter adjustment (%)	113	120	112	115	98	110	107	107	111	106
Normalized difference[e] (%)	17	31	18	22	3	19	16	14	19	9
P from t-test	0.001	0.003	0.003	0.000	0.731	0.028	0.261	0.037	0.000	0.016
Standard error of the mean	5	6	4	3	6	4	7	3	2	2

[a] Tannins, alkaloids, chalcones, stilbenes, flavanones and flavanols, hop acids, coumarins, and aurones.

[b] Anthocyanins, tocopherols and volatiles.

[c] N = Number of data pairs of content of a compound in organic material and corresponding conventional material, from the same species, production site and year, as averages over all reported comparable values for varieties and replications within a study.

[d] Ratio in % = 100 times the content in organic material divided by the content in corresponding conventional material = 100*O/C.

[e] Normalized difference = 100 times (content in organic minus content in conventional) divided by content in conventional = 100*(O-C)/C.

arithmetic averages of several reported values from a study. Information on confidence intervals or other statistical data were not used for the meta-analysis, and therefore also not used as a criterion to select studies to include.

Since, as reported by Woese *et al*. (1997) and Heaton (2001), dry matter content tends to be higher in organically grown plants than in comparable conventionally grown ones, Bourn and Prescott (2002) recommended to express measured values on fresh matter basis. Expression of nutrient content on fresh matter basis is common practice in the area of human nutrition (Food Standards Agency, 2002), because it is generally assumed that humans will consume a constant number of portions of a set weight or volume, so the amount of a vegetable or fruit consumed by humans does not depend critically on dry matter content (although the authors have not been able to locate any literature reporting to have tested this assumption experimentally). In contrast, both in animal nutrition research and in ecological research it is customary to express nutrient content on dry matter basis or energy basis, illustrating an interesting barrier to cross-disciplinary research. From the 67 data pairs for which values for dry matter content was available, an average value for the difference in dry matter content was calculated as the ratio of dry matter content in the organic samples divided by dry matter content in the conventional samples. For those sets of data that were reported only on dry matter basis, the ratios were then adjusted by multiplying with the average difference ratio. The table of extracted values is available on the website of the project 'Meta-analysis of data on composition of organic and conventional foods' (MADOC) (http://research.ncl.ac.uk/madoc/).

To calculate significance and magnitude of differences in contents of the compounds, the ratio (in %) was ln-transformed, and the transformed values were used to determine if the arithmetic average of the ln-transformed ratios were significantly different from ln(100), using resampling (Hedges *et al*., 1999). Back-transformation of these average values provided an estimate of the average difference in content between the systems (Table 3). None of the data points differed so much from other points in the same group that there was a need to exclude outliers (see Figure 1). Despite most of the distributions deviating significantly from a normal distribution, for comparison with other meta-analyses significance was also calculated using a t-test, as well as the average and t-test significances for the normalised differences as used by Worthington (2001) and Dangour *et al.* (2009) (Table 3).

B. Results and Discussion

Of the 102 papers initially identified as relevant, 65 papers met the inclusion criteria, while 37 papers were excluded (Tables 1 and 2). The analysis of secondary metabolites resulted in 275 data pairs, of which 212 were reported on fresh weight basis, while 63 data pairs were provided on dry matter basis. (Table 3, and supplementary material online). For vitamin C, 83 of 86 data pairs were on fresh weight basis.

The average dry matter content of the organic material was 103.4% of the corresponding conventional material, with $P = 0.006$ or $P = 0.0017$ for the significance of this difference, using a t-test or re-sampling test, respectively.

The average differences and significances for each group of compounds are given in Table 3, and illustrated graphically in Figure 1. For vitamin C and all groups of secondary metabolites other than carotenes and the other 'non-defense compounds,' anthocyanins, tocopherols and volatiles, the average content in organic plant material were higher than in the corresponding conventional samples. The secondary metabolites appear to group in three categories corresponding to the functional divisions. The first category comprises defense-related compounds, represented by phenolic acids (group 2) and other defense compounds (group 3) as well as the less well-defined 'total phenolics' (group 1), which show substantially higher contents in organically grown plants than in conventional ones. The second category consists of flavones and flavonols (group 5) and other non-defense-related compounds mostly involved in signalling (color, scent) (group 6), where the differences in content between organic and conventional produce is only slightly higher than the difference in dry matter content, although this still results in a significant difference when calculated on fresh weight basis. Vitamin C, while not a secondary metabolite, shows a similar distribution. The last category are the carotenes (group 4), where it appears that organic products tend to have lower content than the conventional, although the difference was not significant in the present dataset, also not if calculated on dry matter basis (data not shown).

In relation to the ecological relevance, the relatively strong effect for defence related secondary metabolites compared with non-defense-related compounds is completely in line with the theoretical considerations (Stamp, 2003), and matches the effects seen in woody plants, which have been extensively studied in this regard (Koricheva *et al*., 1998; Gayler *et al*., 2004). To the best of the authors' knowledge, the difference in dry matter content between plant material from organic and conventional systems has not been described in the context of ecology or plant physiology, so no explanations or even speculations about the physiological relevance are found in the literature. Scattered data indicate that this may also be a general fertilizer-related effect (Kaack *et al.*, 2001; Norbaek *et al*., 2003), however, it appears that most studies in ecology or plant physiology have not included data on dry matter percentage in their reporting, and therefore not allowed assessment of this effect.

Regarding the risk of bias, in particular publication bias and other forms of unbalanced selection of data, the present study did not attempt to quantitatively assess possible relations between study quality and outcome. However, one indication can be found in the distributions of groups of compounds shown in Figure 1. For the defense-related compounds (1a), there is no indication of a dip around 100% (which would have been expected if lack of significant differences reduced the chance of publication), while this cannot as clearly be ruled out for the non-defense compounds. Another more important indication is the substantial differences between the distributions of groups of compounds with different functions in the plants. Many researchers working on food quality and production systems are familiar with the concept of a relatively high water content in conventional/fast-growing plants, and correspondingly lower content of all other compounds. So this effect, which explains approx. a third of the overall average difference found, could be supported or even caused by a bias towards publication of studies showing the expected results. In contrast, comparatively few researchers in this area are aware that the defence compounds (some of which are considered ‘toxicants’ and therefore undesirable in food) would be expected to be affected differently by differences in growth conditions than non-defense compounds (or even which compounds belong to each of these classes). So the much greater difference between production systems in the content of defense compounds compared with non-defense compounds is unlikely to reflect expectations of researchers or reviewers in the area, indicating that it is much less likely to be caused by bias and thus probably a genuine effect of the growing conditions. Finally, a bias could be caused by researchers more or less intentionally selecting what they considered the best items when they were collecting samples from the system that they believed to be best, and the worst items from the other system. However, since the low content of secondary metabolites are associated with slower growth, a comparison of the largest fruits or vegetables in an organic batch with the smallest from a conventional batch would result in a smaller difference between the compositions than an unbiased selection, while a bias favoring conventional products would increase the difference. In conclusion, it appears to the authors that the most obvious potential forms of bias are unlikely to account for a substantial part of the observed differences, in particular for the defense-related compounds, although this is a question that warrants more detailed analysis in future research.

V. CONSEQUENCES FOR HUMAN HEALTH OF CONSUMING ORGANIC FRUITS AND VEGETABLES

A definitive assessment of the consequences for human health of consuming organic fruits and vegetables would require an intervention study of immense dimensions and cost. One of many steps before embarking on such a challenge is to estimate the likely outcome under as precise as possible assumptions about the mechanisms and magnitudes of effects. The calculations below provide such an estimate, and also point out which assumptions it is based on.

A. Systematic Differences Versus Random Variation

A wide range of external factors influence the composition of plant products, and most of them have much greater effects than the production system effect seen here. Varieties often differ by factors of 2 or 3 in the content of various secondary metabolites (Schindler *et al*., 2005; Kreutzmann *et al*., 2008) and weather/ climate conditions can cause similar variation, as seen when comparing data from different years of the same study (supplementary material online).

Compared with this, the relatively small effect of production system might seem unimportant. However, compared with differences due to climate and soil, which cannot easily be controlled, and differences between varieties, which appear to be random and show no trends across different species, the difference in the content of secondary metabolites between organic and conventional fruits and vegetables is systematic and controllable. The difference in content of secondary metabolites is not sufficiently systematic to be used as a tool for authentication of organic origin, since despite a highly significantly higher average content in the organic samples, in 32% of the data pairs the conventional product had the largest or same value as the organic one (Figure 1). Still, because the production system appears to affect the content of all of the classes of secondary metabolites apart from carotenoids, it is likely that it also affects the largely unknown compounds that are responsible for the health benefits of consumption of fruits and vegetables.

B. Magnitude of Impact on Consumer Health

If a person changes from consuming exclusively conventional fruits and vegetables, to choosing the organic versions of the same products in the same amounts, the intake of all secondary metabolites will increase by approx. 12% (Table 3). From a health perspective, for the reasons provided in section IIIC, it is a reasonable assumption to expect that this would correspond to an increase in the consumption of these foods by 12%. If assuming that the effect is more specifically due to defense-related secondary metabolites, the increase would be even higher, such as 16%. So to set the differences in content in perspective, the question is, how much would such a modest increase in fruit and vegetable intake actually matter for consumer health?

This question has been addressed by Veerman *et al*. (2006), who developed a model to estimate changes in life expectancy caused by changes in fruit and vegetable intake, in relation to assessment of EU policies influencing consumption of vegetables and fruit. The model includes a scenario where an increased intake due to a policy change is proportional to the intake before the change. If there is no change in intake on a g per day basis, and the health impact solely is due to a higher content of the health-beneficial compounds in the food, then the increase in intake of health promoting compounds will be proportional to the habitual intake of fruits and vegetables, so this variant of their model corresponds to a hypothetical situation where consumers change from conventional to organic fruits and vegetables, without changing anything else in their diet or lifestyle. The formula estimated that under these assumptions, in the Dutch population, an increase in the intake of fruit and vegetables of 1.8% would increase life expectancy by 2.6 days for women and 3.8 days for men (Veerman *et al*., 2006). The figures will be slightly different in other populations with different disease patterns and habitual diets. Under the same assumptions, the 12% increase caused by switching to organic fruits and vegetables would correspond to an increase in life expectancy of, on average, 17 days for women and 25 days for men. To put this in perspective, screening for breast cancer has been calculated to provide an average increase in life expectancy of 35 days (Bonneux, 2003), which at the level of the entire population can be considered to be of similar magnitude. Or as another comparison, being overweight by 25 kg will reduce life expectancy by three years (Whitlock *et al.*, 2009), so the 17 days increased life expectancy for women could be described as comparable to the health benefits of a weight loss of 390g, with 570g as the corresponding value for men. This comparison may be particularly relevant, since a likely mechanism for the benefit of increased consumption of vegetables and fruits is the potential ability of defense-related secondary metabolites such as resveratrol to mimic the effect of caloric restriction (Brandt and Mølgaard, 2001), a hypothesis that has subsequently been supported experimentally (Baur and Sinclair, 2006). This effect corresponds with the ecological function of many of these defense compounds to act as antinutrients, making the plant material less attractive to herbivores by reducing their ability to utilize nutrients, thus restricting effective nutrient intake of those who consume foods containing these compounds. It also leads to the interesting possibility that consumers of organic fruits and vegetables may achieve the increased lifespan as a consequence of a corresponding weight loss (or lack of weight gain), which many would consider an added bonus.

The calculations behind these estimates depend on estimates of the relative risks of disease incidences according to fruit and vegetable consumption, most of which are known only with substantial uncertainty (Veerman *et al.*, 2006). It would have been particularly useful to be able to relate the compositional data to more relevant measures of quality of life than simple life expectancy, such as life expectancy after 60 years of age, but such data were not available. Still, by integrating the available data in this way, and identifying the key sources of uncertainty, research can be focused on studies to reduce this uncertainty and thus refine the validity and accuracy of the estimates of benefits.

VI. CONCLUSIONS

The amount of data on compositional differences between organically and conventionally produced fruits and vegetables is now sufficient to not just detect significant differences, but also estimate their magnitude with reasonable precision. The observed differences are that the content of secondary metabolites is approximately 12% higher in organic produce than in corresponding conventional samples, with a larger difference for defense-related compounds and no difference for carotenoids. This corresponds with the predictions from ecology and fertilizer studies, indicating that the differences in content primarily are caused by the differences in fertility management between the systems. If secondary metabolites are responsible for the health promoting effect of consumption of fruits and vegetables, then this means that switching to organic produce will benefit health as much as a 12% increase in intake of fruits and vegetables.

ACKNOWLEDGMENTS

K. Brandt gratefully acknowledges funding in 2007 from the Food and Agriculture Organization of the United Nations (FAO), Rome ($10,000) and the Soil Association, Bristol ($1,000) for review reports that contributed to the basis of the present review.

C. Leifert gratefully acknowledges funding from the European Community under the Sixth Framework Programme for Research, Technological Development and Demonstration Activities, for the Integrated Project QUALITYLOWINPUTFOOD, FP6-FOOD-CT-2003-506358, for the proteomics work.

The authors wish to thank Prof. M. Petticrew, London School of Hygiene and Tropical Medicine, for helpful comments on a draft of the manuscript, and Miss D. Srednicka for assistance with proofreading of the data.

Support is also gratefully acknowledged from The Sheepdrove Trust for the recently commenced project 'Meta-analysis of data on composition of organic and conventional foods' (MADOC), which hosts the website where the dataset used in the present analysis is deposited.

REFERENCES

Abreu, P., Relva, A., Matthew, S., Gomes, Z., and Morais, Z. 2007. High-performance liquid chromatographic determination of glycoalkaloids in potatoes from conventional, integrated, and organic crop systems. *Food Control* **18:** 40–44.

Ali, M., and Tsou, S. C. S. 1997. Combating micronutrient deficiencies through vegetables—A neglected food frontier in Asia. *Food Policy* **22:** 17–38.

Amodio, M. L., Colelli, G., Hasey, J. K., and Kader, A. A. 2007. A comparative study of composition and postharvest performance of organically and conventionally grown kiwifruits. *J. Sci. Food Agric.* **87:** 1228–1236.

Amtmann, A., and Armengaud, P. 2009. Effects of N, P, K and S on metabolism: new knowledge gained from multi-level analysis. *Curr. Opin. Plant Biol.* **12:** 275–283.

Anonymous. 2004. National road map for Integrated Pest Management. http://www.ipmcenters.org/Docs/IPMRoadMap.pdf (accessed November 2009)

Anttonen, M. J., Hoppula, K. I., Nestby, R., Verheul, M. J., and Karjalainen, R. O. 2006. Influence of fertilization, mulch color, early forcing, fruit order, planting date, shading, growing environment, and genotype on the contents of selected phenolics in strawberry (*Fragaria* x *ananassa* Duch.) fruits. *J. Agric. Food Chem.* **54:** 2614–2620.

Anttonen, M. J., and Karjalainen, R. O. 2006. High-performance liquid chromatography analysis of black currant (*Ribes nigrum* L.) fruit phenolics grown either conventionally or organically. *J. Agric. Food Chem.* **54:** 7530–7538.

Asami, D. K., Hong, Y. J., Barrett, D. M., and Mitchell, A. E. 2003. Comparison of the total phenolic and ascorbic acid content of freeze-dried and air-dried marionberry, strawberry, and corn grown using conventional, organic, and sustainable agricultural practices. *J. Agric. Food Chem.* **51:** 1237–1241.

Assured Produce. 2008. Assured Produce Standards. http://www.assuredproduce.co.uk/ap/scheme/standards.aspx (accessed November 2009)

Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, M. J., Aviles-Vazquez, K., Samulon, A., and Perfecto, I. 2007. Organic agriculture and the global food supply. *Renew. Agric. Food Syst.* **22:** 86–108.

Barrett, D. M., Weakley, C., Diaz, J. V., and Watnik, M. 2007. Qualitative and nutritional differences in processing tomatoes grown under commercial organic and conventional production systems. *J. Food Sci.* **72:** C441–C451.

Baur, J. A., and Sinclair, D. A. 2006. Therapeutic potential of resveratrol: the in vivo evidence. *Nature Reviews Drug Discovery* **5:** 493–506.

Baxter, G. J., Graham, A. B., Lawrence, J. R., Wiles, D., and Paterson, J. R. 2001. Salicylic acid in soups prepared from organically and non-organically grown vegetables. *Eur. J. Nut.* **40:** 289–292.

Beltran-Gonzalez, F., Perez-Lopez, A. J., Lopez-Nicolas, J. M., and Carbonell-Barrachina, A. A. 2008. Effects of agricultural practices on instrumental colour, mineral content, carotenoid composition, and sensory quality of mandarin orange juice, cv. Hernandina. *J. Sci. Food Agric.* **88:** 1731–1738.

Benbrook, C. 2007. The Impacts of Yield on Nutritional Quality: Lessons from Organic Farming. *Coll. Crop Yield Qual.* **44:** 12–14.

Benbrook, C., Zhao, X., Davies, N., and Andrews, P. 2008. New Evidence Confirms the Nutritional Superiority of Plant-Based Organic Foods. http://www.organic-center.org/science.nutri.php?action= viewandreport_id=126 (accessed November 2009). The Organic Center.

Biodynamic Agricultural Association 2009. Building long-term soil fertility today. http://www.biodynamic.org.uk/ (accessed November 2009)

Bjelakovic, G., Nikolova, D., Gluud L. L., Simonetti, R. G., and Gluud, C. 2008. Antioxidant supplements for prevention of mortality in healthy participants and patients with various diseases (Review). *Cochrane Libr.* **2:** 1–188.

Bonneux, L. 2003. Mortality reduction by breast-cancer screening. *Lancet* **362:** 245–245.

Bourn, D., and Prescott, J. 2002. A comparison of the nutritional value, sensory qualities, and food safety of organically and conventionally produced foods. *Crit. Rev. Food Sci. Nutr.* **42:** 1–34.

Brandt, K. 2007. Organic agriculture and food utilization. **In**: *Organic Agriculture and Food Security.* pp. 3–33. Scialabba, N. Ed., Food and Agriculture Organization (FAO), Rome. http://www.fao.org/organicag/ofs/docs_en.htm (accessed March 2010)

Brandt, K., Christensen, L. P., Hansen-Møller, J., Hansen, S. L., Haraldsdottir, J., Jespersen, L., Purup, S., Kharazmi, A., Barkholt, V., Frøkiær, H., and Kobæk-Larsen, M. 2004. Health promoting compounds in vegetables and fruits: A systematic approach for identifying plant components with impact on human health. *Trends Food Sci. Techn.* **15:** 384–393.

Brandt, K., and Mølgaard, J. P. 2001. Organic agriculture: does it enhance or reduce the nutritional value of plant foods? *J. Sci. Food Agric.* **81**: 924–931.

Briviba, K., Stracke, B. A., Rufer, C. E., Watzl, B., Weibel, F. P. and Bub, A. 2007. Effect of consumption of organically and conventionally produced apples on antioxidant activity and DNA damage in humans. *J. Agric. Food Chem.* **55:** 7716–7721.

Camin, F., Moschella, A., Miselli, F., Parisi, B., Versini, G., Ranalli, P., and Bagnaresi, P. 2007. Evaluation of markers for the traceability of potato tubers grown in an organic versus conventional regime. *J. Sci. Food Agric.* **87:** 1330–1336.

Carbonaro, M., and Mattera, M. 2001. Polyphenoloxidase activity and polyphenol levels in organically and conventionally grown peach (*Prunus persica* L., cv. Regina bianca) and pear (*Pyrus communis* L., cv. Williams). *Food Chem.* **72:** 419–424.

Carbonaro, M., Mattera, M., Nicoli, S., Bergamo, P., and Cappelloni, M. 2002. Modulation of antioxidant compounds in organic vs conventional fruit (peach, *Prunus persica* L., and pear, *Pyrus communis* L.). *J. Agric. Food Chem.* **50:** 5458–5462.

Caris-Veyrat, C., Amiot, M. J., Tyssandier, V., Grasselly, D., Buret, M., Mikolajczak, M., Guilland, J. C., Bouteloup-Demange, C., and Borel, P. 2004. Influence of organic versus conventional agricultural practice on the antioxidant microconstituent content of tomatoes and derived purees; Consequences on antioxidant plasma status in humans. *J. Agric. Food Chem.* **52:** 6503–6509.

Cayuela, J. A., Vidueira, J. M., Albi, M. A., and Gutierrez, F. 1997. Influence of the ecological cultivation of strawberries (*Fragaria x Ananassa* Cv Chandler) on the quality of the fruit and on their capacity for conservation. *J. Agric. Food Chem.* **45:** 1736–1740.

Chassy, A. W., Bui, L., Renaud, E. N. C., van Horn, M., and Mitchell, A. E. 2006. Three-year comparison of the content of antioxidant microconstituents and several quality characteristics in organic and conventionally managed tomatoes and bell peppers. *J. Agric. Food Chem.* **54:** 8244–8252.

Chiesa, A., Frezza, D., Moccia, S., Oberti, A., Fraschina, A., and Diaz, L. 2005. Vegetable production technology and postharvest quality. *Proc. 5th Int. Postharvest Symp.* **1-3:** 565–572.

Chinnici, F., Bendini, A., Gaiani, A., and Riponi, C. 2004. Radical scavenging activities of peels and pulps from cv. Golden Delicious apples as related to their phenolic composition. *J. Agric. Food Chem.* **52:** 4684–4689.

Daiss, N., Lobo, M. G., and Gonzalez, M. 2008. Changes in postharvest quality of Swiss chard grown using 3 organic preharvest treatments. *J. Food Sci.* **73:** S314–S320.

Dangour, A. D., Dodhia, S. K., Hayter, A., Allen, E., Lock, K., and Uauy, R. 2009. Nutritional quality of organic foods: a systematic review. *Am. J. Clin. Nutr.* **90:** 680–685.

Dani, C., Oliboni, L. S., Vanderlinde, R., Bonatto, D., Salvador, M., and Henriques, J. A. P. 2007. Phenolic content and antioxidant activities of white and purple juices manufactured with organically- or conventionally-produced grapes. *Food Chem. Tox.* **45:** 2574–2580.

Dauchet, L., Amouyel, P., and Dallongeville, J. 2009. Fruits, vegetables and coronary heart disease. *Nature Rev. Cardiol.* **6:** 599–608.

de Jong, T. J. 1995. Why fast-growing plants do not bother about defence. *Oikos* **74:** 545–548.

de Pascale, S., Tamburrino, R., Maggio, A., Barbieri, G., Fogliano, V., and Pernice, R. 2006. Effects of nitrogen fertilization on the nutritional value of organically and conventionally grown tomatoes. *Acta Hort.* **700:** 107–110.

Ekelund, L., and Tjarnemo, H. 2004. Consumer preferences for organic vegetables — The case of Sweden. *Proc. Xvth Int. Symp. Hort. Econ. Man.* 121–128.

Englund, G., Sarnelle, O., and Cooper, S. D. 1999. The importance of data-selection criteria: Meta-analyses of stream predation experiments. *Ecology* **80:** 1132–1141.

EUREPGAP 2004. EUREPGAP Fruit and Vegetables. http://www.eurepgap.org/fruit/documents.html (accessed November 2009)

European Commission 2007. Council Regulation (EC) No. 834/2007. http://ec.europa.eu/agriculture/organic/eu-policy/legislation_en (accessed November 2009)

Faller, A. L. K., and Fialho, E. 2009. The antioxidant capacity and polyphenol content of organic and conventional retail vegetables after domestic cooking. *Food Res. Int.* **42:** 210–215.

Fauriel, J. B., Plénet, D., and Amiot, M.-J. 2005. Can a peach production in organic farming be requalified with polyphenols? A comparative case study in Rhône-Alpes Region (France). http://orgprints.org/6850/ (accessed November 2009)

Fauriel, J. B., Plenet, D., and Amiot, M.-J. 2007. On-farm influence of production patterns on total polyphenol content in peach. **In:** *3rd QLIF Congress.* pp. 122–125. Niggli, U., Leifert, C., Alföldi, T., Lück, L., and Willer, H., Eds., Hohenheim, Germany.

Ferreres, F., Valentao, P., Llorach, R., Pinheiro, C., Cardoso, U., Pereira, J. A., Sousa, C., Seabra, R. M., and Andrade, P. B. 2005. Phenolic compounds in external leaves of tronchuda cabbage (*Brassica oleracea* L. *var. costata* DC). *J. Agric. Food Chem.* **53:** 2901–2907.

Fjelkner-Modig, S., Bengtsson, H., Stegmark, R., and Nystrom, S. 2001. The influence of organic and integrated production on nutritional, sensory and agricultural aspects of vegetable raw materials for food production. *Acta Agric. Scand. Sect. B - Soil Plant Sci.* **50:** 102–113.

Flores, P., Hellin, P., and Fenoll, J., 2009a. Effect of manure and mineral fertilisation on pepper nutritional quality. *J. Sci. Food Agric.* **89:** 1581–1586.

Flores, P., Hellin, P., Lacasa, A., Lopez, A., and Fenoll, J. 2009b. Pepper mineral composition and sensory attributes as affected by agricultural management. *J. Sci. Food Agric.* **89:** 2364–2371.

Food Standards Agency 2002. McCance and Widdowson's The Composition of Foods integrated dataset (CoF IDS). http://www.food.gov.uk/science/dietarysurveys/dietsurveys/#h_2 (accessed November 2009)

Forster, M. P., Rodriguez, E. R., and Romero, C. D. 2002. Differential characteristics in the chemical composition of bananas from Tenerife (Canary Islands) and Ecuador. *J. Agric. Food Chem.* **50:** 7586–7592.

Fritz, C., Palacios-Rojas, N., Feil, R., and Stitt, M. 2006. Regulation of secondary metabolism by the carbon-nitrogen status in tobacco: nitrate inhibits large sectors of phenylpropanoid metabolism. *Plant J.* **46:** 533–548.

Gayler, S., Leser, C., Priesack, E., and Treutter, D. 2004. Modelling the effect of environmental factors on the "trade-off" between growth and defensive compounds in young apple trees. *Trees Struc. Funct.* **18:** 363–371.

Gaziano, J. M., Glynn, R. J., Christen, W. G., Kurth, T., Belanger, C., MacFadyen, J., Bubes, V., Manson, J. E., Sesso, H. D., and Buring, J. E. 2009. Vitamins E and C in the Prevention of Prostate and Total Cancer in Men. The Physicians' Health Study II Randomized Controlled Trial. *JAMA* **301:** 52–62.

Gennaro, L., and Quaglia, G. B. 2002. Food safety and nutritional quality of organic vegetables. **In:** *6th International Symposium on Protected Cultivation in Mild Winter Climate.* pp. 675–680.

Gobbo-Neto, L., and Lopes, N. P. 2007. Medicinal plants: Factors of influence on the content of secondary metabolites. *Quimica Nova* **30:** 374–381.

Grinder-Pedersen, L., Rasmussen, S. E., Bügel, S., Jørgensen, L. V., Dragsted, L. O., Gundersen, V., and Sandström, B. 2003. Effect of diets based on foods from conventional versus organic production on intake and excretion of flavonoids and markers of antioxidative defense in humans. *J. Agric. Food Chem.* **51:** 5671–5676.

Hajšlová, J., Schulzová, V., Slanina, P., Janne, K., Hellenäs, K. E., and Andersson, C. 2005. Quality of organically and conventionally grown potatoes: Four-year study of micronutrients, metals, secondary metabolites, enzymic browning and organoleptic properties. *Food Add. Contam.* **22:** 514–534.

Hakkinen, S. H., and Torronen, A. R. 2000. Content of flavonols and selected phenolic acids in strawberries and *Vaccinium* species: influence of cultivar, cultivation site and technique. *Food Res. Int.* **33:** 517–524.

Hallmann, E.R. and Rembialkowska, E. 2007. Comparison of the Nutritive Quality of Tomato Fruits from Organic and Conventional Production in Poland. http://orgprints.org/9944/ (accessed November 2009)

Hamouz, K. Lachman, J., Dvořák, P., and Pivec, V. 2005. The effect of ecological growing on the potatoes yieldand quality. *Plant Soil Environ.* **51:** 6.

Hargreaves, J., Adl, M. S., Warman, P. R., and Rupasinghe, H. P. V. 2008. The effects of organic amendments on mineral element uptake and fruit quality of raspberries. *Plant and Soil* **308:** 213–226.

Harker, F. R. 2004. Organic food claims cannot be substantiated through testing of samples intercepted in the marketplace: a horticulturalist's opinion. *Food Qual. Pref.* **15:** 91–95.

Heaton, S. 2001. Organic farming, food quality and human health. A review of the evidence. http://www.soilassociation.org/Whyorganic/Health/Reports/tabid/388/Default.aspx Accessed November 2009.

Hecke, K., Herbinger, K., Veberic, R., Trobec, M., Toplak, H., Stampar, F., Keppel, H., and Grill, D. 2006. Sugar-, acid- and phenol contents in apple cultivars from organic and integrated fruit cultivation. *Eur. J. Clin. Nutr.* **60:** 1136–1140.

Hedges, L. V., Gurevitch, J., and Curtis, P. S. 1999. The meta-analysis of response ratios in experimental ecology. *Ecology* **80:** 1150–1156.

Heimler, D., Isolani, L., Vignolini, P., and Romani, A. 2009. Polyphenol content and antiradical activity of *Cichorium intybus* L. from biodynamic and conventional farming. *Food Chem.* **114:** 765–770.

Hoare, J., Henderson, L., Bates, C. J., Prentice, A., Birch, M., Swan, G., and Farron, M. 2004. National Diet and Nutrition Survey: Adults Aged 19 to 64 Years. vol. 5: Summary report. http://www.food.gov.uk/science/dietarysurveys/ndnsdocuments/ndnsvol52004 Accessed November 2009.

IFOAM 2005. The Principles of Organic Agriculture. http://www.ifoam.org/about_ifoam/principles/index.html Accessed November 2009.

Ismail, A., and Fun, C. S. 2003. Determination of vitamin C, β-carotene and riboflavin contents in five green vegetables organically and conventionally grown. *Malays. J. Nutr.* **9:** 31–39.

Juhler, R. K., Larsen, S. B., Meyer, O., Jensen, N. D., Spano, M., Giwercman, A., and Bonde, J. P., 1999. Human semen quality in relation to dietary pesticide exposure and organic diet. *Arch. Env. Cont. Tox.* **37:** 415–423.

Juroszek, P., Lumkin, H. M., Yang, R. Y., Ledesma, D. R., and Ma, C. H. 2009. Fruit quality and bioactive compounds with antioxidant activity of tomatoes grown on-farm: Comparison of organic and conventional management systems. *J. Agric. Food Chem.* **57:** 1188–1194.

Kaack, K., Nielsen, M., Christensen, L. P., and Thorup-Kristensen, K. 2001. Nutritionally important chemical constituents and yield of carrot (*Daucus carota* L.) roots grown organically using ten levels of green manure. *Acta Agric. Scand. Sect. B - Soil Plant Sci.***51:** 125–136.

Kahu, K., Janes, H., Luik, A., and Klaas, L. 2009. Yield and fruit quality of organically cultivated blackcurrant cultivars. *Acta Agric. Scand.Sect. B - Soil Plant Sci.***59:** 63–69.

de Keukeleire, J., Janssens, I., Heyerick, A., Ghekiere, G., Cambie, J., Roldan-Ruiz, I., van Bockstaele, E., and de Keukeleire, D. 2007. Relevance of organic farming and effect of climatological conditions on the formation of alpha-acids, beta-acids, desmethylxanthohumol, and xanthohumol in hop (*Humulus lupulus* L.). *J. Agric. Food Chem.* **55:** 61–66.

Koh, E., Wimalasiri, K. M. S., Renaud, E. N. C., and Mitchell, A. E. 2008. A comparison of flavonoids, carotenoids and vitamin C in commercial organic and conventional marinara pasta sauce. *J. Sci. Food Agric.* **88:** 344–354.

Koricheva, J., Larsson, S., Haukioja, E., and Keinanen, M. 1998. Regulation of woody plant secondary metabolism by resource availability: hypothesis testing by means of meta-analysis. *Oikos* **83:** 212–226.

Kovacevic, D. B., Vahcic, N., Levaj, B., and Uzelac, V. D. 2008. The effect of cultivar and cultivation on sensory profiles of fresh strawberries and their purees. *Flav. Fragr. J.* **23:** 323–332.

Kreutzmann, S., Christensen, L. P., and Edelenbos, M. 2008. Investigation of bitterness in carrots (*Daucus carota* L.) based on quantitative chemical and sensory analyses. *Food Sci. Techn.* **41:** 193–205.

Lairon, D. 2010. Nutritional quality and safety of organic food. A review. In *Agron. Sust. Dev.* **30:** 33–41.

Lambers, H., Mougel, C., Jaillard, B., and Hinsinger, P. 2009. Plant-microbe-soil interactions in the rhizosphere: an evolutionary perspective. *Plant Soil* **321:** 83–115.

Lamperi, L., Chiuminatto, U., Cincinelli, A., Galvan, P., Giordani, E., Lepri, L., and del Bubba, M. 2008. Polyphenol levels and free radical scavenging activities of four apple cultivars from integrated and organic farming in different Italian areas. *J. Agric. Food Chem.* **56:** 6536–6546.

Lee, S. K., and Kader, A. A. 2000. Preharvest and postharvest factors influencing vitamin C content of horticultural crops. *Posth Biol. Techn.* **20:** 207–220.

Lehesranta, S. J., Koistinen, K. M., Massat, N., Davies, H. V., Shepherd, L. V. T., McNicol, J. W., Cakmak, I., Cooper, J., Luck, L., Karenlampi, S. O., and Leifert, C. 2007. Effects of agricultural production systems and their components on protein profiles of potato tubers. *Proteomics* **7:** 597–604.

Leiss, K. A., Maltese, F., Choi, Y. H., Verpoorte, R., and Klinkhamer, P. G. L. 2009. identification of chlorogenic acid as a resistance factor for thrips in *chrysanthemum*. *Plant Physiol.* **150:** 1567–1575.

Lester, G. E., Manthey, J. A., and Buslig. B. S. 2007. Organic vs conventionally grown Rio Red whole grapefruit and juice: Comparison of production inputs, market quality, consumer acceptance, and human health-bioactive compounds. *J. Agric. Food Chem.* **55:** 4474–4480.

Levite, D., Adrian, M., and Tamm, L. 2000. Preliminary Results on Contents of Resveratrol in Wine of Organic and Conventional Vineyards. http://orgprints.org/9107/ Accessed November 2009.

Lima, G. P. P., da Rocha, S. A., Takaki, M., Ramos, P. R. R., and Ono, E. O. 2008. Comparison of polyamine, phenol and flavonoid contents in plants grown under conventional and organic methods. *Int. J. Food Sci. Techn.* **43:** 1838–1843.

Lima, G. P. P., Lopes, T. D. C., Rossetto, M. R. M., and Vianello, F. 2009. Nutritional composition, phenolic compounds, nitrate content in eatable vegetables obtained by conventional and certified organic grown culture subject to thermal treatment. *Int. J. Food Sci. Techn.* **44:** 1118–1124.

Lin, J., Cook, N. R., Albert, C., Zaharris, E., Gaziano, J. M., van Denburgh, M., Buring, J. E., and Manson, J. E. 2009. Vitamins C and E and beta carotene supplementation and cancer risk: A randomized controlled trial. *J. Nat. Cancer Inst.* **101:** 14–23.

Linseisen, J., Rohrmann, S., Miller, A. B., Bueno-de-Mesquita, H. B., Buchner, F. L., and Riboli, E. 2007. Fruit and vegetable consumption and lung cancer risk: Updated information from the European Prospective Investigation into Cancer and Nutrition (EPIC). *Int. J. Cancer* **121:** 1103–1114.

Lombardi-Boccia, G., Lucarini, M., Lanzi, S., Aguzzi, A., and Cappelloni, M. 2004. Nutrients and antioxidant molecules in yellow plums (*Prunus domestica* L.) from conventional and organic productions: A comparative study. *J. Agric. Food Chem.* **52:** 90–94.

Lumpkin, H. 2005. A comparison of lycopene and other phytochemicals in tomatoes grown under conventional and organic management systems. *AVRDC Tech. Bull*. **34:** 1–60.

Lundberg, J. O., Weitzberg, E., and Gladwin, M. T. 2008. The nitrate-nitrite-nitric oxide pathway in physiology and therapeutics. *Nature Rev. Drug Disc.* **7:** 156–167.

Magkos, F., Arvaniti, F., and Zampelas, A. 2003. Organic food: nutritious food or food for thought? A review of the evidence. *Int. J. Food Sci. Nutr.* **54:** 357–371.

Malusa, E., Laurenti, E., Ghibaudi, E., and Rolle, L. 2004. Influence of organic and conventional management on yield and composition of grape cv. ‘Grignolino’. *Acta Hort.* **640:** 135–141.

Marin, A., Gil, M. I., Flores, P., Hellin, P., and Selma, M. V. 2008. Microbial Quality and Bioactive Constituents of Sweet Peppers from Sustainable Production Systems. *J. Agric. Food Chem.* **56:** 11334–11341.

Masamba, K. G., and Nguyen, M. 2008. Determination and comparison of vitamin C, calcium and potassium in four selected conventionally and organically grown fruits and vegetables. *Afr. J. Biotech.* **7:** 2915–2919.

Matallana, G. C., Hurtado, C., and Martínez, T. J. 1998. Study of water-soluble vitamins (thiamin, riboflavin, pyridoxine and ascorbic acid) in ecologically-grown lettuce (*Lactuca sativa* L.). *Alimentaria* **35:** 39–43.

McKnight, G. M., Duncan, C. W., Leifert, C., and Golden, M. H. 1999. Dietary nitrate in man: friend or foe? *Brit. J. Nutr.* **81:** 349–358.

Mendez, C. D. V., Forster, M. P., Rodriguez-Delgado, M. A., Rodriguez-Rodriguez, E. M., and Romero, C. D. 2003. Content of free phenolic compounds in bananas from Tenerife (Canary Islands) and Ecuador. *Eur. Food Res. Techn.* **217:** 287–290.

Meyer, M., and Adam, S. T. 2008. Comparison of glucosinolate levels in commercial broccoli and red cabbage from conventional and ecological farming. *Eur. Food Res. Techn.* **226:** 1429–1437.

Mikkonen, T. P., Maatta, K. R., Hukkanen, A. T., Kokko, H. I., Torronen, A. R., Karenlampi, S. O., and Karjalainen, R. O. 2001. Flavonol content varies among black currant cultivars. *J. Agric. Food Chem.* **49:** 3274–3277.

Mitchell, A. E., Hong, Y. J., Koh, E., Barrett, D. M., Bryant, D. E., Denison, R. F., and Kaffka, S. 2007. Ten-year comparison of the influence of organic and conventional crop management practices on the content of flavonoids in tomatoes. *J. Agric. Food Chem.* **55:** 6154–6159.

Mogren, L. M., Caspersen, S., Olsson, M. E., and Gertsson, U. 2008. Organically fertilized onions (*Allium cepa* L.): Effects of the fertilizer placement method on quercetin content and soil nitrogen dynamics. *J. Agric. Food Chem.* **56:** 361–367.

Moreira, M.D., Roura, S.I., and del Valle, C. E. 2003. Quality of Swiss chard produced by conventional and organic methods. *Food Sci. Techn.* **36:** 135–141.

Mozafar, A. 1993. Nitrogen fertilizers and the amount of vitamins in plants - a review. *J. Plant Nutr.* **16:** 2479–2506.

Mulero, J., Pardo, F., and Zafrilla, P. 2009. Effect of principal polyphenolic components in relation to antioxidant activity in conventional and organic red wines during storage. *Eur. Food Res. Techn.* **229:** 807–812.

Murthy, N. S., Mukherjee, S., Ray, G., and Ray, A. 2009. Dietary factors and cancer chemoprevention: An overview of obesity-related malignancies. *J. Postgrad. Med.* **55:** 45–54.

Nobili, F., Finotti, E., Foddai, M. S., Azzini, E., Garaguso, I., Raguzzini, A., Tisselli, V., Piazza, C., Durazzo, A., and Maiani, G. 2008. Bioactive compounds in tomatoes: effect of organic vs. conventional management in Parma in 2006. http://orgprints.org/11902 (accessed November 2009)

Norbæk, R., Aaboer, D. B. F., Bleeg, I. S., Christensen, B. T., Kondo, T., and Brandt, K. 2003. Flavone C-glycoside, phenolic acid, and nitrogen contents in leaves of barley subject to organic fertilization treatments. *J. Agric. Food Chem.* **51:** 809–813.

Olsson, M. E., Andersson, C. S., Oredsson, S., Berglund, R. H., and Gustavsson, K. E. 2006. Antioxidant levels and inhibition of cancer cell proliferation in vitro by extracts from organically and conventionally cultivated strawberries. *J. Agric. Food Chem.* **54:** 1248–1255.

Ordonez-Santos, L. E., Arbones-Macineira, E., Fernandez-Perejon, J., Lombardero-Fernandez, M., Vazquez-Oderiz, L., and Romero-Rodriguez, A. 2009. Comparison of physicochemical, microscopic and sensory characteristics of ecologically and conventionally grown crops of two cultivars of tomato (*Lycopersicon esculentum* Mill.). *J. Sci. Food Agric.* **89:** 743–749.

Osenberg, C. W., Sarnelle, O., Cooper, S. D., and Holt, R. D. 1999. Resolving ecological questions through meta-analysis: Goals, metrics, and models. *Ecology* **80:** 1105–1117.

Palit, S., Ghosh, B. C., Gupta, S. D., and Swain, D. K. 2008. Studies on tea quality grown through conventional and organic management practices: Its impact on antioxidant and antidiarrhoeal activity. *Trans. Asabe* **51:** 2227–2238.

Peck, G. M., Andrews, P. K., Reganold, J. P., and Fellman, J. K. 2006. Apple orchard productivity and fruit quality under organic, conventional, and integrated management. *Hortsci.* **41:** 99–107.

Perez-Lopez, A. J., del Amor, F. M., Serrano-Martinez, A., Fortea, M. I., and Nunez-Delicado, E. 2007a. Influence of agricultural practices on the quality of sweet pepper fruits as affected by the maturity stage. *J. Sci. Food Agric.* **87:** 2075–2080.

Perez-Lopez, A. J., Lopez-Nicolas, J. M., and Carbonell-Barrachina, A. A. 2007b. Effects of organic farming on minerals contents and aroma composition of Clemenules mandarin juice. *Eur. Food Res. Techn.* **225:** 255–260.

Perez-Lopez, A. J., Lopez-Nicolas, J. M., Nunez-Delicado, E., del Amor, F. M., and Carbonell-Barrachina, A. A. 2007c. Effects of agricultural practices on color, carotenoids composition, and minerals contents of sweet peppers, cv. Almuden. *J. Agric. Food Chem.* **55:** 8158–8164.

Pieper, J. R., and Barrett, D. M. 2009. Effects of organic and conventional production systems on quality and nutritional parameters of processing tomatoes. *J. Sci. Food Agric.* **89:** 177–194.

Rapisarda, P., Calabretta, M. L., Romano, G., and Intrigliolo, F. 2005. Nitrogen metabolism components as a tool to discriminate between organic and conventional citrus fruits. *J. Agric. Food Chem.* **53:** 2664–2669.

Rembialkowska, E. 1999. Comparison of the contents of nitrates, nitrites, lead, cadmium and vitamin C in potatoes from conventional and ecological farms. *Pol. J. Food Nutr. Sci.* **8:** 17–26.

Rembialkowska, E. 2007. Quality of plant products from organic agriculture. *J. Sci. Food Agric.* **87:** 2757–2762.

Rembialkowska, E., Hallmann, E., and Rusakzonek, A. 2007. Influence of processing on bio-active substances content and anti-oxidant properties of apple puree from organic and conventional production in Poland. **In:** *3rd QLIF Congress*. pp. 139–143. Niggli, U., Leifert, C., Alföldi, T., Lück, L., and Willer, H., Eds., Hohenheim, Germany.

Ren, H. F., Endo, H., and Hayashi, T. 2001. Antioxidative and antimutagenic activities and polyphenol content of pesticide-free and organically cultivated green vegetables using water-soluble chitosan as a soil modifier and leaf surface spray. *J. Sci. Food Agric.* **81:** 1426–1432.

Riu-Aumatell, M., Castellari, M., Lopez-Tamames, E., Galassi, S., and Buxaderas, S. 2004. Characterisation of volatile compounds of fruit juices and nectars by HS/SPME and GUMS. *Food Chem.* **87:** 627–637.

Robbins, R.J., Keck, A.S., Banuelos, G., and Finley, J. W. 2005. Cultivation conditions and selenium fertilization alter the phenolic profile, glucosinolate, and sulforaphane content of broccoli. *J. Med. Food* **8:** 204–214.

Rodriguez, J., Rios, D., Rodriguez, D., and Diaz, C. 2006. Physico-chemical changes during ripening of conventionally, ecologically and hydroponically cultivated Tyrlain (TY 10016) tomatoes. *Int. J. Agric. Res.* **1:** 452–461.

Rossi, F., Godani, F., Bertuzzi, T., Trevisan, M., Ferrari, F., and Gatti, S. 2008. Health-promoting substances and heavy metal content in tomatoes grown with different farming techniques. *Eur. J. Nut.* **47:** 266–272.

Sanford, L. L., Deahl, K. L., Sinden, S. L., and Ladd, T. L. 1992. Glycoalkaloid contents in tubers from *Solanum tuberosum* populations selected for potato leafhopper resistance. *Am. Potato J.* **69:** 693–703.

Santamaria, P. 2006. Nitrate in vegetables: toxicity, content, intake and EC regulation. *J. Sci. Food Agric.* **86:** 10–17.

Schifferstein, H. N. J., and Ophuis, P. A. M. O. 1998. Health-related determinants of organic food consumption in the Netherlands. *Food Qual. Pref.* **9:** 119–133.

Schindler, M., Solar, S., and Sontag, G. 2005. Phenolic compounds in tomatoes. Natural variations and effect of gamma-irradiation. *Eur. Food Res. Techn.* **221:** 439–445.

Schulzová, V. and Hajšlová, J. 2007. Biologically active compounds in tomatoes from various fertilisation systems. **In:** *3rd QLIF Congress*. pp. 144–147. Niggli, U., Leifert, C., Alföldi, T., Lück, L., and Willer, H., Eds., Hohenheim, Germany.

Sousa, C., Pereira, D. M., Pereira, J. A., Bento, A., Rodrigues, M. A., Dopico-Garcia, S., Valentao, P., Lopes, G., Ferreres, F., Seabra, R. M., and Andrade, P. B. 2008. Multivariate analysis of tronchuda cabbage (*Brassica oleracea* L. *var. costata* DC) phenolics: Influence of fertilizers. *J. Agric. Food Chem.* **56:** 2231–2239.

Sousa, C., Valentao, P., Rangel, J., Lopes, G., Pereira, J. A., Ferreres, F., Seabra, R. A., and Andrade, P. B. 2005. Influence of two fertilization regimens on the amounts of organic acids and phenolic compounds of tronchuda cabbage (*Brassica oleracea* L. *var. costata* DC). *J. Agric. Food Chem.* **53:** 9128–9132.

Stamp, N. 2003. Out of the quagmire of plant defense hypotheses. *Quart. Rev. Biol.* **78:** 23–55.

Stracke, B. A., Rufer, C. E., Bub, A., Briviba, K., Seifert, S., Kunz, C., and Watzl, B., 2009a. Bioavailability and nutritional effects of carotenoids from organically and conventionally produced carrots in healthy men. *Brit. J. Nutr.* **101:** 1664–1672.

Stracke, B. A., Rufer, C. E., Weibel, F. P., Bub, A., and Watzl, B. 2009b. Three-year comparison of the polyphenol contents and antioxidant capacities in organically and conventionally produced apples (*Malus domestica* Bork. cultivar 'Golden Delicious'). *J. Agric. Food Chem.* **57:** 4598–4605.

Tarozzi, A., Hrelia, S., Angeloni, C., Morroni, F., Biagi, P., Guardigli, M., Cantelli-Forti, G., and Hrelia, P. 2006. Antioxidant effectiveness of organically and non-organically grown red oranges in cell culture systems. *Eur. J. Nut.* **45:** 152–158.

Tarozzi, A., Marchesi, A., Cantelli-Forti, G., and Hrelia, P. 2004. Cold-storage affects antioxidant properties of apples in caco-2 cells. *J. Nutr.* **134:** 1105–1109.

Tinttunen, S., and Lehtonen, P. 2001. Distinguishing organic wines from normal wines on the basis of concentrations of phenolic compounds and spectral data. *Eur. Food Res. Techn.* **212:** 390–394.

Toor, R. K., Savage, G. P., and Heeb, A. 2006. Influence of different types of fertilisers on the major antioxidant components of tomatoes. *J. Food Comp. Anal.* **19:** 20–27.

USDA 2009. National Organic Program (NOP) http://www.ams.usda.gov/AMSv1.0/NOP Accessed November 2009.

Valavanidis, A., Vlachogianni, T., Psomas, A., Zovoili, A., and Siatis, V. 2009. Polyphenolic profile and antioxidant activity of five apple cultivars grown under organic and conventional agricultural practices. *Int. J. Food Sci. Techn.* **44:** 1167–1175.

Veberic, R., Trobec, M., Herbinger, K., Hofer, M., Grill, D., and Stampar, F. 2005. Phenolic compounds in some apple (*Malus domestica* Borkh) cultivars of organic and integrated production. *J. Sci. Food Agric.* **85:** 1687–t1694.

Veerman, J. L., Barendregt, J. J., and Mackenbach, J. P. 2006. The European Common Agricultural Policy on fruits and vegetables: exploring potential health gain from reform. *Eur. J. Pub. Health* **16:** 31–35.

Versari, A., Parpinello, G. P., Mattioli, A. U., and Galassi, S. 2008. Characterisation of Italian commercial apricot juices by high-performance liquid chromatography analysis and multivariate analysis. *Food Chem.* **108:** 334–340.

Vian, M. A., Tomao, V., Coulomb, P. O., Lacombe, J. M., and Dangles, O. 2006. Comparison of the anthocyanin composition during ripening of Syrah grapes grown using organic or conventional agricultural practices. *J. Agric. Food Chem.* **54:** 5230–5235.

Wang, S. Y., Chen, C. T., Sciarappa, W., Wang, C. Y., and Camp, M. J. 2008. Fruit quality, antioxidant capacity, and flavonoid content of organically and conventionally grown blueberries. *J. Agric. Food Chem.* **56:** 5788–5794.

Warman, P. R., and Havard, K. A. 1997. Yield, vitamin and mineral contents of organically and conventionally grown carrots and cabbage. *Agric. Ecosys. Env.* **61:** 155–162.

Warman, P. R., and Havard, K. A. 1998. Yield, vitamin and mineral contents of organically and conventionally grown potatoes and sweet corn. *Agric. Ecosys. Env.* **68:** 207–216.

Weibel, F. P., Bickel, R., Leuthold, S., Alfoldi, T., and Niggli, U. 1998. Are organically grown apples tastier and healthier? A comparative field study using conventional and alternative methods to measure fruit quality. **In:** *12th International IFOAM Scientific Conference*. pp. 147–153.

Whitlock, G., Lewington, S., Sherliker, P., Clarke, R., Emberson, J., Halsey, J., and Aric, P. C. 2009. Body-mass index and cause-specific mortality in 900 000 adults: collaborative analyses of 57 prospective studies. *Lancet* **373:** 1083–1096.

Williams, C. M. 2002. Nutritional quality of organic food: shades of grey or shades of green? *Proc. Nutr. Soc.* **61:** 19–24.

Winter, C. K., and Davis, S. F. 2006. Organic foods. *J. Food Sci.* **71:** R117-R124.

Winter, J. W., Paterson, S., Scobie, G., Wirz, A., Preston, T., and McColl, K. E. L. 2007. N-nitrosamine generation from ingested nitrate via nitric oxide in subjects with and without gastroesophageal reflux. *Gastroent.* **133:** 164–174.

Woese, K., Lange, D., Boess, C., and Bogl, K. W. 1997. A comparison of organically and conventionally grown foods - Results of a review of the relevant literature. *J. Sci. Food Agric.* **74:** 281–293.

Worthington, V. 2001. Nutritional quality of organic versus conventional fruits, vegetables, and grains. *J. Alt. Compl. Med.* **7:** 161–173.

Wszelaki, A. L., Delwiche, J. F., Walker, S. D., Liggett, R. E., Scheerens, J. C., and Kleinhenz, M. D. 2005. Sensory quality and mineral and glycoalkaloid concentrations in organically and conventionally grown redskin potatoes (*Solanum tuberosum*). *J. Sci. Food Agric.* **85:** 720–726.

Wunderlich, S. M., Feldman, C., Kane, S., and Hazhin, T. 2008. Nutritional quality of organic, conventional, and seasonally grown broccoli using vitamin C as a marker. *Int. J. Food Sci. Nutr.* **59:** 34–45.

Yanez, J. A., Miranda, N. D., Remsberg, C. A., Ohgami, Y., and Davies, N. M. 2007. Stereospecific high-performance liquid chromatographic analysis of eriodictyol in urine. *J. Pharm. Biomed. Anal.* **43:** 255–262.

Yanez, J. A., Remsberg, C. M., Miranda, N. D., Vega-Villa, K. R., Andrews, P. K., and Davies, N. M. 2008. Pharmacokinetics of selected chiral flavonoids: Hesperetin, naringenin and eriodictyol in rats and their content in fruit juices. *Biopharm. Drug Disp.* **29:** 63–82.

Yildirim, H.K., Akcay, Y.D., Guvenc, U., and Sozmen, E.Y. 2004. Protection capacity against low-density lipoprotein oxidation and antioxidant potential of some organic and non-organic wines. *Int. J. Food Sci. Nutr.* **55:** 351–362.

Yiridoe, E. K., Bonti-Ankomah, S., and Martin, R. C. 2005. Comparison of consumer perceptions and preference toward organic versus conventionally produced foods: A review and update of the literature. *Renew. Agric. Food Syst.* **20:** 193–205.

Young, J. E., Zhao, X., Carey, E. E., Welti, R., Yang, S. S., and Wang, W. Q. 2005. Phytochemical phenolics in organically grown vegetables. *Mol. Nutr. Food Res.* **49:** 1136–1142.

Zafrilla, P., Morillas, J., Mulero, J., Cayuela, J.M., Martinez-Cacha, A., Pardo, F., and Nicolas, J. M. L. 2003. Changes during storage in conventional and ecological wine: Phenolic content and antioxidant activity. *J. Agric. Food Chem.* **51:** 4694–4700.

Zhao, X., Carey, E. E., Young, J.E., Wang, W. Q., and Iwamoto, T. 2007. Influences of organic fertilization, high tunnel environment, and postharvest storage on phenolic compounds in lettuce. *Hortsci.* **42:** 71–76.

Zhao, X., Nechols, J. R., Williams, K. A., Wang, W. Q., and Carey, E. E. 2009. Comparison of phenolic acids in organically and conventionally grown pac choi (*Brassica rapa* L. *chinensis*). *J. Sci. Food Agric.* **89:** 940–946.

Critical Reviews in Plant Sciences, 30:198–225, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554492

Edible and Tended Wild Plants, Traditional Ecological Knowledge and Agroecology

Nancy J. Turner,[1] Łukasz Jakub Łuczaj,[2] Paola Migliorini,[3] Andrea Pieroni,[3] Angelo Leandro Dreon,[4] Linda Enrica Sacchetti,[4] and Maurizio G. Paoletti[4]
[1]*School of Environmental Studies, University of Victoria, British Columbia, Canada V8P 2C9*
[2]*Department of Ecotoxicology, University of Rzeszów, Werynia, 36–100 Kolbuszowa, Poland*
[3]*University of Gastronomic Sciences, Via Amedeo di Savoia 8, I-12060 Pollenzo/Bra, Italy*
[4]*Laboratory of Agroecology and Ethnobiology, Department of Biology, University of Padova, Via G. Colombo 3, 35131 Padova, Italy*

Table of Contents

Address correspondence to Nancy J. Turner, School of Environmental Studies, University of Victoria, British Columbia, Canada V8W 3R4. E-mail: nturner@uvic.ca

Referee: Sally L. Benjamin, M.S., J.D., Ecologist, Science Program Development USG, Northern Prairie Wildlife Research Center, 871137th Street SE, Jamestown, ND 58401-7317.

Humans the world over have depended on wild-growing plants in their diets for hundreds of thousands of years, and many people continue to rely on these species to meet at least part of their daily nutritional needs. Wild harvested plant foods include: roots and other underground parts; shoots and leafy greens; berries and other fleshy fruits; grains, nuts and seeds; and mushrooms, lichens, algae and other species. Use of any of these species requires special cultural knowledge regarding harvesting, preparation, cooking and other forms of processing. Many were, and are, prepared and served in mixtures or combinations. In most cases, too, the species are managed, tended or manipulated in some way to increase their productivity and availability. Many of the most widely used species are categorized as weeds—species that grow and reproduce readily in disturbed or cleared land, and are common around human settlements and agricultural areas. This paper presents case examples of edible wild plant use and the roles of these species in agroecosystems from different parts of the world and discusses similarities and differences in use across different cultures and segments of society.

Keywords edible wild plants, foraging, edible weeds, root vegetables, wild berries, wild greens

I. INTRODUCTION

Humans have depended on edible wild plants, along with diverse wild insects, birds, fish, and mammals and their products, for the vast part of our history. Between approximately 20% and 30% of the plants on the planet (ca. 280,000 described species) and possibly 30% to 50% of mushroom species have some parts that have been eaten or that have been assumed to be palatable and edible (e.g., providing nutrients and generally assumed to be safe for consumption). As well, most small or very small animals such as invertebrates have been considered edible, especially in the tropics. But it is not true that all invertebrates are edible or have been chosen as food. Humans vary considerably in their food choices. For example, different human groups living in similar or only slightly different environments—especially in the tropical forests and savannas such as in Alto Orinoco, but also in rural areas—utilize quite a different basket of species.

These differences have been explained from territorial differences and different levels of availability of foods, and extreme biodiversity. These arguments, however, though valid, do not provide the overall explanation. In most cases the landscapes utilized by different ethnic groups for foraging are quite similar, and the different choices of species for food can be due to necessity or opportunity rather than through conflict in resource adoption across different groups. In addition, an attitude is suggested to allow choices from the potentially available biodiversity of a set of species that are acceptable within a group and have acquired status within small human communities over time (Paoletti, 2005; Paoletti and Dufour, 2005).

Here we have collected worldwide ideas about the assemblage of plants from the wild that are traditionally collected especially by local traditional communities in rural, forested, wetland, and montane areas. These species might be considered as “wild edibles” only if they are being collected without particular manipulation. In reality, however, as Posey (Posey and Plenderleith, 2004; Paoletti, 2004; Malaisse, 1997) and many other researchers (e.g., Anderson, 2005; Deur and Turner, 2005; Minnis and Elisens, 1999) have documented, most activities of hunter collectors (and horticulturists) in the Amazon and many other parts of the world, including temperate regions, include direct or indirect manipulation of resource species and habitats. Relying on their accumulated traditional knowledge and observations, indigenous people attend to many key plants and insects, such as ants, producing a sort of semidomestication or paradomestication process (i.e., caring for and promoting *in situ*) that is underway in most cases even if difficult to characterize. In addition, many semidomesticated crops are only locally known and would need more selection and genetic work to be promoted as domesticated crops (NAC, 1989).

Only within the last 10,000 years or so have we started to focus on domestication—genetically altering species significantly from their wild-growing ancestors—as a major process in food production. People domesticated suites of plants in different parts of the world within more or less the same time period from about 9,000 to 5,000 years ago: barley, wheat, rye, figs, and grapes from the Middle East; corn, dry beans, and tomatoes from Mexico; potatoes and peanuts from Andean South America; rice and oranges from Southeast Asia, and so forth. In most parts of the world, however, until very recently, people continued to rely on wild plants in their natural habitats to provide a major portion of their food. For example, Ötzi, a Neolithic (5,200-year-old) mountain traveler known as the “ice man,” whose frozen body was found in 1991 in the Tyrolean Alps at the border of Italy and Austria, was carrying sloe plums (*Prunus spinosa*) with him. He probably also would have eaten wild hazelnuts (*Corylus avellana*), wild raspberries (*Rubus idaeus*) and fruits of the wayfaring tree (*Viburnum lantana*), as well as a variety of wild-growing greens and wild game (Dickson *et al*., 2003). Wild plant species, even for agrarian peoples or pastoralists who mainly used animal products, would have assumed a special importance during times of crop failure and famine (Turner and Davis, 1993). Some of these are the species that we know of today as "weeds": species well adapted to disturbed conditions and often associated with human habitation. In turn, some of these weeds became the candidates for domestication: for example, mustards (*Brassica* spp.), wild carrot (*Daucus carota*), chicory (*Cichorum intybus*) and lettuce (*Lactuca* spp.).

Altogether, widely used domesticated species comprise only a fraction of the 20,000 or so plant species known to have been used as food by humans (Paoletti, 2004; Piperno and Pearsall, 1998). Canadian Indigenous peoples alone have used over 500 species of plants for food (Kuhnlein and Turner, 1991). In recent times, however, especially in urban areas of the world, most people have come to depend on fewer and fewer species to provide them with their daily nutrition. Today, only around 20 domesticated species supply up to 85% of the world's food base. Yet, the potential for more intensively using, and possibly further domesticating, a wide diversity of wild-growing plant species is immense.

In this chapter, we describe and provide examples of various categories of edible wild and tended and/or semidomesticated plants used by Indigenous and local peoples in different parts of the world. We then discuss the concept of tending and managing wild plants, fungi and algae. Many different types of edible species, while not domesticated in the sense of dramatic genetic alterations through successive selective breeding, are nonetheless enhanced in quality and productivity through directed human activities, ranging from selective harvesting and thinning, to pruning and coppicing, to controlling pests and removing competing species. Sometimes termed collectively "incipient agriculture," these practices are effective management strategies in their own right, and in some cases have been in place in a given area for millennia (Smith, 2005). Many of the species that are tended are woody or herbaceous perennials, which are "kept living" and producing sometimes over many years or even generations (Deur and Turner, 2005). The types of wild food plants in diverse ecosystems throughout the world are described next, with regional patterns and trends in edible plant groups. "Weeds" are another focus of this chapter. As noted previously, weedy species are well represented in the larder of edible wild-growing plants, many having long associations with humans, and serving not only to provide edible roots, greens and seeds, but also form the basis of many medicinal preparations, featuring strongly in the history of medicine (Stepp and Moerman, 2004).

Many people do not realize or appreciate the extent to which edible wild plants continue to contribute to peoples' nutritional and dietary needs, even in parts of Europe. As a demonstration of their importance, a case study of edible wild plant use in Mediterranean regional cuisine is offered, focusing on inland Southern Italy. The richness and diversity of wild foods, their contributions to local economies, and their diverse modes of preparation are emphasized. Wild food plants contribute more than nutrients; for many people and ethnic groups, the use of wild foods is a source of cultural identity, reflecting a deep and important body of knowledge about the environment, survival, and sustainable living known widely as traditional ecological knowledge. This important relationship is discussed, followed by concluding comments on the future of wild plant food use in a changing world. Along with the major sections of the chapters, we provide a series of examples of a range of important but diverse aspects of wild food use.

II. CATEGORIES OF EDIBLE WILD PLANTS

Edible wild plants include food categories familiar to everyone: "root vegetables" (including true roots and underground storage organs like bulbs, corms, tubers and rhizomes); edible greens (leaves, stems, shoots, including marine algae); fleshy fruits (berries, pomes, drupes); and grains, seeds, and nuts. Other edible products include inner bark and cambium of trees, plant-based beverages, plants used for flavoring, and edible wild mushrooms and lichens (biologically different from plants but usually considered together with them). Many of these wild foods are common and productive, as well as being highly nutritious, palatable and easily harvested. Some, such as *Rubus* spp. (raspberry relatives) and *Rosa* spp. (wild roses), yield more than one type of food, in these cases both edible fruits and edible green shoots. Wild-growing plants, together with wild-harvested fish, shellfish and game, have sustained relatively large populations for many thousands of years, from the Northwest Coast of North America to Amazonia in South America, to Eastern Africa: in fact, across every continent except Antarctica (FAO, 1988; Hedrick, 1972; Hussain, 1987; Pieroni, 2005; Kuhnlein *et al.,* 2009, in press; Balée, 1994; Szczawinski and Turner, 1978, 1980; Turner and Szczawinski, 1978, 1979; Walsh, 2009).

Examples of diverse edible wild plant genera and species used in different parts of the world are provided in Table 1, and are described in general in the following sections. Nutritional values for many wild food species can be found in Kuhnlein and Turner (1991; now available in digital form through FAO, 2009).

A. Root Vegetables (Roots, Corns, Tubers and Rhizomes)

Root vegetables, like fruits and greens, are ancient human foods. Kubiak-Martens (1996) documented the presence of tissues of two edible root genera possibly used as food by Palaeolithic and Mesolithic peoples from the site of Całowanie in the central part of the Polish Plain: arrowleaf, wapato, or "swamp potato" (*Sagittaria* sp.) and tuberous bistort (*Polygonum* sp.). Many different indigenous groups in eastern Asia and North America are known to have used species in these genera as food (especially *S. sagittifolia* and *S. latifolia*; and *P. bistorta* and *P. vivipara*) (Arnason *et al.,* 1981; Kuhnlein and Turner, 1991; Strecker, 2007). *Sagittaria latifolia* is known to have very high starch content (ca. 55.0% of dry matter), and in some parts of western North America, the tubers were the most important source of carbohydrates for indigenous peoples, and were a favoured staple food (Kuhnlein and Turner, 1991; Darby, 1996).

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997).

Root vegetables (roots, bulbs, corms, tubers and rhizomes)

Allium spp. (onions, garlic); Liliaceae—temperate prairies, bluffs, woodlands; N Hemisphere; many species eaten, usually after cooking, throughout various parts of the world.

Amphicarpa bracteata (hog peanut); Fabaceae—deciduous woods and clearings, E N America; tuberous roots cooked and eaten by First Peoples.

Arctium lappa and other spp. (burdock); Asteraceae—woods and disturbed ground, Eurasia; introduced in N America; first-year taproot highly valued in Japan (fried); in England ingredient of homemade beer.

Arum italicum and other spp. (lords-and-ladies); Araceae—woods and hedgerows, western Europe and the Mediterranean; starch-rich tubers an important famine food throughout the area.

Argentina anserina, A. egedii (syn. *Potentilla*) (silverweed, cinquefoil); Rosaceae—moist meadows, saline marshes, tidal flats, river and lake margins, temperate and boreal regions, N America, N Europe, Asia, Himalayas; fleshy taproots cooked and eaten by N American First Peoples, and in UK, Tibet and elsewhere.

Balsamorhiza sagittata (balsamroot, or spring sunflower); Asteraceae—open woods, sagebrush steppe, and subalpine meadows, NW N America; taproots pit-cooked and eaten; also young shoots, budstalks and seeds eaten.

Bunium bulbocastanum (pignut); Apiaceae—grasslands, Eurasia; tubers eaten boiled in some parts of Europe.

Butomus umbellatus (flowering rush); Butomaceae—water margins, Eurasia; rhizomes made into flour or cooked, particularly in Siberia.

Camassia spp. (edible camas); Liliaceae—temperate woodlands, oak parklands, W N America; bulbs cooked and eaten by many Indigenous peoples as a staple; main carbohydrate is inulin, a complex sugar based on fructose units.

Campanula rapunculus (rampion); Campanulaceae—herbaceous biennial of gravelly pastures, roadsides and along hedge-banks, of Europe and UK; formerly widely grown for its edible roots, which have a pleasant sweet flavour reminiscent of walnuts (leaves also eaten); traditionally collected in Ligurian region.

Chaerophyllum bulbosum (bulbous chervil); Apiaceae—herbaceous biennial or perennial of river margins, roadsides in Eurasia, and introduced in parts of N America; tubers eaten raw throughout Eastern Europe.

Cirsium spp. (thistles); Asteraceae—herbaceous perennials of open, disturbed ground and old fields, widespread, N America and Eurasia; taproots of several spp. eaten by N American First Peoples; main carbohydrate is inulin; green stalks peeled and eaten in Spain, Portugal and elsewhere.

Claytonia spp. (spring beauty); Portulacaceae—herbaceous perennials of temperate woodlands, subalpine meadows, prairies, N America, NE Asia; corms cooked and eaten by many peoples.

Cordyline spp. (ti, cabbage tree); Laxmanniaceae, flaxlike leaves borne in tufts; cooked roots of several spp. eaten by Maori and other Polynesians; *C. terminalis* has domesticated forms that were used in molasses production and for making alcoholic beverages.

Corydalis solida (fumewort); Fumariaceae—herbaceous perennial of woods and steppe, Europe and N Asia; bulbs eaten after cooking by Kalmucks and Russians.

Dioscorea spp. (yams); Dioscoreaceae—herbaceous perennial of tropical and subtropical forests, Africa, S Asia, New Guinea, Australia; tuberous roots a very important source of nutrition for forest dwelling indigenous peoples; used after prolonged processing.

Dryopteris expansa (spiny wood fern); Dryopteridaceae—moist open forest, avalanche runs, circumpolar region; rootstocks pit-cooked or steamed and eaten by First Peoples of NW N America.

Elymus repens (couchgrass, or quackgrass); Poaceae—perennial grass of fields and river margins, widespread in Europe; rhizomes dried and powdered into flour, rich in carbohydrates; used mainly as an ingredient of bread and soups, many northern and central European countries (e.g. Poland and Germany).

Equisetum arvense (common horsetail); Equisetaceae—weedy perennial of open ground and arable fields, circumpolar; little tubers eaten throughout northern hemisphere, particularly in Russia.

Erythronium spp. (glacier lily, avalanche lily, fawn lily); Liliaceae—bulb-forming perennial of open woods and meadows, N America, E Asia; bulbs of various spp. cooked and eaten in Japan, Korea, NW N America.

Fritillaria camschatcensis, Fritillaria spp. (riceroot); Liliaceae—salt marshes, shorelines, prairies, dry open bluffs, W N America, Kamchatka; ricelike bulbs steamed and eaten by Pacific Rim First Peoples.

(Continued on next page)

TABLE 1
Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al*., 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Helianthus tuberosus (Jerusalem artichoke, sunchoke); Asteraceae—tuberous perennial of open woodlands, wet meadows, N America; tubers contain inulin as major carbohydrate; eaten raw and cooked.

Hedysarum alpinum (Eskimo Potato, licorice root, Indian carrot); Fabaceae—herbaceous perennial of moist open woods and meadows, Arctic and S in mountains; long roots eaten raw or cooked (WARNING, similar species are toxic).

Lathyrus tuberosus (tuberous pea) and related species e.g. *L. linifolius*; Fabaceae—herbaceous perennial of open ground, Europe; tubers eaten raw as a valued snack.

Leopoldia comosa (syn: *Muscari comosum*); Liliaceae—herbaceous perennial of arable fields, Europe; bulbs consumed since long time in the Eastern Mediterranean (after maceration in cold water for decreasing the bitterness), esp. Southern Italy, Albania, and Greece; Nowadays widely cultivated for serving these markets in Morocco and Algeria.

Lewisia rediviva (bitterroot); Portulacaceae—herbaceous perennial of open pine woods, sagebrush desert, W N America; taproots steamed and eaten by Plateau indigenous peoples.

Lilium columbianum, *L. cordatum* and other spp. (lilies); Liliaceae—herbaceous perennials of open woods and meadows, N America, E Asia; starchy bulbs cooked and eaten by indigenous peoples.

Lomatium spp. (biscuitroots, kous); Apiaceae—taprooted or tuberous rooted herbaceous perennials of dry plains and open wood and meadows, northwestern N America; tuberous roots cooked and eaten by indigenous peoples.

Microseris lanceolata (murnong or yam daisy); Asteraceae—taprooted herbaceous perennial of dry open plains and forest edges, widespread in Australia and Tasmania; fleshy taproots pit-roasted and eaten by Indigenous Australians.

Nelumbo nucifera and other spp. (lotus); Nelumbonaceae—rhizomatous aquatic perennial of Asia and elsewhere; fleshy rhizomes eaten as a cooked vegetable in soups and a variety of other dishes; seeds also widely eaten.

Nuphar lutea (yellow pondlily); Nymphaeaceae—rhizomatous perennial of ponds and lakes; widespread in Northern Hemisphere; fleshy rhizomes eaten by some indigenous peoples in North America and Eurasia; after cooking or other preparation.

Nymphaea spp. (waterlily); Nymphaeaceae—rhizomatous perennial of ponds and lakes; cosmopolitan genus; fleshy rhizomes eaten by indigenous people in some regions, e.g., Australia, after prolonged preparation.

Orchis spp. (orchid); Orchidaceae—herbaceous perennial of grasslands and woods; Eurasia; underground parts made into a food called *salep*; eaten mainly in SE Europe and SW Asia, also in England.

Polygonatum spp. (Solomon’s seal); Convallariaceae—herbaceous rhizomatous perennial of woods and clearings; widespread in Northern Hemisphere; fleshy rhizomes cooked and eaten by indigenous peoples in North America and Eurasia, particularly in China and Japan.

Polygonum vivaparum (alpine bistort); Polygonaceae—herbaceous perennial of montane meadows and northern tundra, circumpolar; rhizomes eaten by northern First Peoples; in Eurasia also *P. bistorta* (bistort) and related spp. eaten.

Polypodium spp. (polypody); Polypodiaceae—woods, particularly on rocks or old trees, widespread in northern hemisphere; rhizome eaten raw or added as sweetener; they have a high sugar content; being the sweetest "root" of the northern hemisphere; used e.g., in Italy, Poland, Slovakia, Norway, Balkans, as well as on the western coast of North America.

Pteridium aquilinum (bracken fern); Dennstaedtiaceae—herbaceous perennial fern of meadows, open woods and clearings, widespread and ubiquitous; starchy rhizomes roasted and eaten; sometimes pounded into flour by indigenous peoples of NW N America and elsewhere (but potentially carcinogenic).

Sagittaria spp. (wapato, arrowhead); Alismataceae—herbaceous perennial of wetlands, marshes and lake edges, widespread, N America and Eurasia; starchy tubers cooked and eaten as a staple vegetable.

Stachys palustris (marsh woundwort); Lamiaceae—herbaceous perennial and arable weed of river margins and marshes, widespread in northern Europe; rhizomes dried and powdered into flour or rhizomes eaten cooked, sometimes raw; used in northern Europe (mainly in Poland) until the turn of the 19th and 20th century.

Trifolium wormskioldii (springbank clover); Fabaceae—herbaceous perennial of moist meadows and coastal regions, tidal marshes, W North America; rhizomes steamed and eaten by NW Coast First Peoples.

Typha spp. (cattail, bulrush); Typhaceae—herbaceous perennial of wetlands, lakeshores, worldwide; starchy rhizomes cooked and eaten by many people; sometimes rendered into flour (young green shoots, immature flowering spikes, seeds and pollen also eaten).

(Continued on next page)

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Edible greens (leaves, stems, shoots, including marine algae)

Adansonia digitata (baobab); Malvaceae—broad-leaved tree of E Africa; one of the most important edible wild greens of African indigenous peoples.

Allium ursinum (ramsons), *A. victorialis*; Liliaceae—herbaceous perennials, found in many parts of northern Eurasia; leaves and stalks, raw, cooked or lacto-fermented; *A. ursinum* used in Europe, *A. victorialis* in Asia (Siberia, Central Asia, Korea); both species are an important ingredient of Russian cuisine, called *cheremsha*); many *Allium* spp. eaten throughout N hemisphere.

Amaranthus spp. (amaranth, pigweed); Amaranthaceae—disturbed ground, moist clearings; widespread in many parts of the world; greens eaten as a boiled vegetable, in curry, soups, etc. (seeds also edible and nutritious).

Arctium lappa (great burdock); Asteraceae—large-leaved biennial growing up to 2 m; Eurasia; young leaves and stalks eaten raw or cooked; traditionally collected in Ligurian region (taproots also eaten in Asia).

Aruncus dioicus (goatsbeard); Rosaceae—tall herbaceous perennial of moist forest edges and streamsides, Eurasia and N America; young edible stems and leaves eaten as asparagus; traditionally collected in Friuli Venezia Giulia and Veneto region.

Asparagus racemosus, Asparagus spp. (wild asparagus); Liliaceae—tall herbaceous perennials of moist open woods to dry clearings; widespread, Europe, Asia, naturalized in N America; tender young shoots eaten after cooking.

Balsamorhiza sagittata (balsamroot or spring sunflower); Asteraceae—open slopes, upland meadows, sagebrush plains, W N America; young shoots and budstalks eaten raw or cooked by First Peoples (pit-cooked taproots and seeds also edible).

Bambusa spp., *Phyllostachys* spp. and other spp. (bamboo shoots); Poaceae—tropical and subtropical forests, various parts of SE and E Asia, tree- or shrub-like grass; young shoots boiled and eaten as popular vegetable in E Asia; WARNING: some bamboo shoots contain toxic levels of cyanide-producing compounds.

Beta vulgaris (including ssp. *cicla, B. hortensis*, (spinach beet, chard); Chenopodiaceae—herbaceous annual or biennial of Europe; leaves and leaf stems eaten raw or cooked like spinach; traditionally collected in Ligurian region.

Borago officinalis (wild borage); Boraginaceae—herbaceous annual of roadsides and arable fields in Europe, naturalized in many other areas in the world; young leaves commonly used in Mediterranean cuisine; flowers also edible; traditionally collected in Ligurian region.

Bunias orientalis (warty cabbage, Turkish rocket); Brassicaceae—herbaceous perennial of northern Eurasia and introduced elsewhere; young stalks commonly eaten in Russia and Romania, raw or boiled.

Campanula trachelium (campanula); Campanulaceae—herbaceous perennial of woodlands; leaves boiled in spring; mixture called “pistic” of Friuli Venezia Giulia region.

Capsella bursa-pastoris (shepherd’s purse); Brassicaceae—basal leaves highly valued for stir-fries and dumplings in Eastern Asia; young fruits eaten as children’s snack in Europe; plant used as food in vegetable dish called “pistic” (Val Colvera pre Alpine zone of Friuli Venezia Giulia).

Carlina acaulis (stemless carline thistle); Asteraceae—herbaceous perennial of disturbed sites, Europe; raw and boiled blossoms; traditionally collected in Western Friuli region.

Centranthus ruber (red valerian); Valerianaceae—boiled leaves; young leaves are used for salads. The cold rootstock brew is used to treat digestive problems and anxiety. It is generally used as a heart-calming agent. The older leaves are boiled. This plant is included in the blend of Levanto’s *gattafin*. Taste: bitter; traditionally collected in Ligurian region; plant included in the “preboggion” (or “prebuggiun”) blend.

Chenopodium album and other species (lamb’s quarters, goosefoot); Chenopodiaceae—mainly as arable weeds, Eurasia; young shoots and leaves used to be the most important wild green of eastern Europe; also eaten in E Asia. Ingredient of “pistic” and “preboggion” blend.

Cicerbita alpina (blue sow thistle); Asteraceae—eaten especially as young stem as asparagus preserved under oil or vinegar. Traditionally collected in Western Friuli.

Chenopodium bonus henricus (Good King Henry); Chenopodiaceae—Europe, W Asia, N America; roadsides; young plants, leaves cooked after snow melting; plant included in “pistic” blend.

Cichorium intybus (wild chicory); Asteraceae—roadside, Europe, N America; native to central Russia, W Asia, S Europe whorls very commonly eaten (cooked) as greens in the whole Mediterranean; leaves—raw or cooked; young leaves in salad; the roasted root is used as a substitute coffee; traditionally collected in Ligurian region; plant included in the “preboggion” blend.

(Continued on next page)

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Cirsium spp. (thistles); Asteraceae—herbaceous perennials of Eurasia and N America; young leaves of numerous species eaten in S, C & E Europe and in eastern Asia. Plant included in the “preboggion” and “pistic” blend.

Crepis spp. (Hawksbeard); Asteraceae—boiled leaves traditionally collected in N Italy and consumed in soups.

Cynara cardunculus (wild artichoke); Asteraceae—arable fields, roadside, S Europe; the stalks, roots, and flower receptacles are very appreciated (boiled) in the traditional cuisine of the Mediterranean area.

Chamerion angustifolium (syn. *Epilobium angustifolium*) (fireweed); Onagraceae—widespread in disturbed ground, open woods, burns and clearings, circumpolar; young shoots, stems, flowering tops eaten.

Diplazium esculentum (vegetable fern); Athyriaceae—a fern from subtropical and tropical forests; SE Asia, Oceania; young fronds widely consumed as a vegetable, often sold in SE Asian markets.

Diplotaxis tenuifolia (perennial wall rocket); Brassicaceae—S C Europe; leaves raw used in salad.

Equisetum arvense (common horsetail); Equistaceae—widespread in moist and disturbed areas, open woods, circumpolar; young shoots eaten raw or cooked in Japan and NW N America, formerly also in Russia and Poland.

Euterpa oleracea, *Bacris gasipaes*, *Daemonorops schmidtiana* and other spp. (palm hearts); Arecaceae—tropical forests, C and S America (including Amazonia); young apical shoots eaten locally and exported as canned product.

Foeniculum vulgare (fennel); Apiaceae—young leaves and stem—eaten raw or cooked, seeds are used as a flavoring in castagnaccio cakes; traditionally collected in the Mediterranean area; in the Ligurian region plant is included in the “prebuggiun” blend.

Heracleum maximum, H. sphondylium s.l. (cow-parsnip); Apiaceae—temperate deciduous and coniferous forests, N America and Eurasia; young, peeled budstalks and leafstalks eaten by Indigenous peoples (WARNING: skin and hairs contain phototoxins, irritating to the skin when exposed to sunlight); in E Europe was widely used to make lacto-fermented soup called *barshch* or *borsh.*

Humulus lupulus (Hop); Cannabaceae—W Asia, Europe; hedgerows; sprouts cooked in the Spring mixture or with omelettes.

Hypochaeris spp. (*H. radicata, H. maculata*) (common cat’s ear); Asteraceae—boiled leaves; plant included in the “preboggion” and “pistic” blends.

Hyoseris radiata (Radicchio selvatico); Asteraceae– boiled leaves; traditionally collected in Ligurian region; plant included in the “preboggion” blend.

Lactuca spp. (*L. serriola, L. perennis*) (prickly lettuce); Asteraceae - S C Europe, N Africa, Himalayas; young leaves raw or cooked.

Lamium spp. (dead nettle); Lamiaceae—small perennials or annuals, temperate forests, meadow and arable fields; used cooked, mainly in the past, Europe and Japan. In particulary *Lamium purpureum* is included in the “pistic” blend.

Lomatium nudicaule (Indian celery, barestem lomatium); Apiaceae—open bluffs, meadows, woodlands, W N America; young leaves and stalks eaten fresh or cooked; rich in vitamin C.

Leontodon hispidus (rough hawkbit) - Asteraceae—Europe, Caucasus and Iran; Ligurian use: young leaves - raw or cooked; plant included in “preboggion” and “pistic blends.”

Matteuccia struthiopteris (ostrich fern); Dryopteridaceae—temperate deciduous and coniferous forests, E (and W) N America, Japan, Asia; fiddlehead shoots eaten; wild–harvested and marketed as specialty food.

Metroxylon sagu and other spp. (sago palm); Arecaceae—swampy to dry tropical forests, Malaysia and Indonesia, Papua New Guinea; starchy inner core a staple for many forest peoples. To this palm, palmworms are associated as additional harvest especially in Papua New Guinea.

Opuntia spp. (prickly pear cactus, “Indian fig”); Cactaceae—deserts and open dry lands, W and SW N America, Mexico, C America; fleshy stem segments de-spined, cooked and eaten (fruits also eaten fresh and raw or as preserves, both in the Americas and naturalized in the Mediterranean region).

Origanum heracleuticum (wild oregano); Lamiaceae—arable fields in S Europe; flowering tops gathered during the summer and used worldwide as a seasoning for the real Italian pizza.

Ornithogalum pyrenaicum (Bath asparagus); Liliaceae—woods and scrub; S Europe; leaves and blossoms boiled in the spring mixture; traditionally collected in Friuli Venezia Giulia region.

Oxyria digyna (mountain sorrel); Polygonaceae—rocky upland sites, circumpolar regions; leaves eaten raw and cooked; rich in vitamin C, acidic due to oxalic acid.

(Continued on next page)

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Palmaria palmata (red seaweed, dulse); Rhodymeniaceae—temperate coastline, N temperate zone; whole plant harvested, dried, eaten raw as a snack, or cooked in soup.

Papaver somniferum (opium poppy); Papaveraceae—young plants, leaves cooked in the spring mixture; plant included in the "pistic" blend.

Papaver rhoeas (corn poppy); Papaveraceae—Europe, N Africa, Asia; boiled leave; traditionally collected in Ligurian region and ingredient of "preboggion."

Petasites japonicus (Japanese coltsfoot, fuki); Asteraceae—moist deciduous forests, Japan, Sakhalin Islands; leafstalks boiled, peeled, eaten as a springtime green as side dish or in soup.

Phyteuma spicatum (Spiked rampion); Campanulaceae—leaves and blossoms boiled in the spring mixture; traditionally collected in Friuli Venezia Giulia region.

Porphyra abbottiae (red laver seaweed) and *Porphyra* spp.; Porphyraceae—rocky coastline, intertidal zone, W coast of N America (*P. abbottiae*) and N and S temperate zones; harvested dried and served as snack, in soup or dishes with fish eggs; considered a health food.

Ranunculus ficaria (lesser celandine); Ranunculaceae—woods and hedges, mainly in Europe; young leaves eaten raw or as potherb in central Europe (e.g. Slovakia, Romania, Ukraine); boiled leaves in the spring mixture "pistic" (Friuli Venezia Giulia region) and "preboggion" (Ligurian region).

Reichardia picroides (French scorzonera); Asteraceae—S Europe; leaves eaten raw in salads or cooked; traditionally collected in Ligurian region; plant included in the "preboggion" blend.

Rubus spp. (thimbleberry, salmonberry); Rosaceae—W N America, moist, open woodlands and clearings, young shoots harvested in spring, peeled and eaten with oil or fish eggs by NW Coast First Peoples.

Rumex arcticus and other *Rumex* spp. (sourdock, wild rhubarb); Polygonaceae—clearings, disturbed ground, circumboreal, northern regions; leaves and stems eaten, fermented, boiled, fresh by Inuit and other First Peoples.

Ruscus aculeatus (butcher's broom); Liliaceae—W S Europe; shoots boiled or preserved under oil.

Salix alexensis, *S. pulchra* (Alaska willow, sura willow); Salicaceae—moist rocky ground, circumpolar, northern taiga and tundra; leaves and shoots eaten by Inuit as fresh green; rich in Vitamin C.

Sanguisorba minor (salad burnet); Rosaceae—Mediterranean countries, Asia Minor, Iraq, Iran, Afghanistan, cultivated in Europe; boiled leaves or leaf salad; taste: slightly bitter; traditionally collected in Ligurian region.

Silene vulgaris (bladder campion); Caryophyllaceae—N Africa, Asia, arable fields, Europe. The young shoots are appreciated (boiled) in the cuisine of Southern Europe; Ligurian use : boiled leaves or leaf salad; plant of the "preboggion" blend; boiled sprouts or leaves in the spring mixture "pistic".

Scolymus hispanicus (Spanish oyster thistle); Asteraceae—arable fields, roadside, Europe; the midribs boiled and eaten as artichokes in many areas in the Mediterranean.

Sonchus oleraceus (sow thistle); Asteraceae—roadside Europe, N Africa, Asia; young leaves very commonly eaten (generally cooked) as greens in the Mediterranean; tender leaflets are used in salads or boiled. Taste: slightly bitter, with hazelnut flavor; traditionally collected in Ligurian region; boiled leaves in "pistic."

Sonchus asper (prickly sow thistle); Asteraceae—Eurasia, Africa; leaves boiled in "pistic" blend.

Stanleya pinnata (prince's plume); Brassicaceae—tall subshrub of desert regions of SW N America; young leaves eaten as greens by indigenous peoples of Great Basin.

Stellaria media (chickweed); Caryophyllaceae—a small annual of arable fields; young plants eaten in soups and as potherb by farming communities of Eurasia, mainly in the past; ingredient of "pistic."

Taraxacum officinalis (dandelion); Asteraceae—Leaves raw and cooked; traditionally collected in Liguria.

Tragopogon pratensis (goat's beard); Asteraceae—Europe, Caucasus, Siberia, Iran; meadows, dunes, roadsides; leaves, root and stem; young leaves raw or boiled.

Ulmus spp. (elm); Ulmaceae—trees from northern hemisphere; leaves used in many regions as famine food; young fruits used as a green vegetable in China.

(Continued on next page)

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Urtica dioica (stinging nettle); Urticaceae—temperate coniferous and deciduous forests and nearby clearings, N Temperate region; young shoots eaten as potherb, used to make tea, sauce.

Valerianella spp. (wild corn salad); Valerianaceae –arable fields in Europe, N Africa, and W Asia; leaves very appreciated in salads in many local cuisines.

Berries and other fleshy fruits

Actinidia spp. (kiwi, Chinese gooseberry); Actinidiaceae—many species, of warm temperate and subtropical forests, SW China, E Asia; introduced to New Zealand in early 1900s; flavorful, fleshy fruits eaten, some (kiwifruit) cultivated; most with wild–collected fruits.

Adansonia digitata (baobab); Malvaceae—E Africa; fleshy fruits valued throughout Africa; raw or the pup used to make beverages; oil from seeds.

Amelanchier alnifolia (Saskatoon berry, serviceberry, Juneberry); Rosaceae—deciduous shrub of open woods, slopes and clearings, W N America; other spp. in E N America; pomes sweet and juicy, eaten fresh, cooked, dried; some forms now under cultivation in W Canada.

Amelanchier ovalis (Snowy mespilus); Rosaceae—C S Europe; fruits eaten raw.

Bactris gasipaes (peach palm); Arecaceae—a tropical palm; S and Central America; fruits widely eaten throughout the area, one of the most important fruits of many forest–dwelling groups, e.g., Huaorani in Ecuador.

Berberis vulgaris (barberry); Berberidaceae—N Europe; roadsides; sprouts, leaves and fruits raw or cooked.

Celtis spp. (hackberry); Cannabaceae—trees, deciduous forests, often along rivers, a few dozen species, mainly in warmer temperate parts of Northern Hemisphere; locally eaten raw in N. America, southern Europe and E Asia.

Cornus spp. (dogwood); Cornaceae—shrubs, forests and scrub, northern hemisphere, some species of the genus bear tasty fruits used locally (e.g. *C. mas* in SE Europe and Caucasus, *C. canadensis, C. suecica, C. kousa*), while others are bitter or even slightly toxic (*C. alba, C. stolonifera*).

Cornus mas (Cornelian cherry); Cornaceae—Europe; fruits raw, fermented in water to produce an alcoholic wine and vinegar.

Crataegus spp. (hawthorn); Rosaceae—deciduous shrub, most temperate regions of the world; fruits eaten raw or processed worldwide.

Dillenia indica (elephant apple); Dilleniaceae—a tree from forests of S and SE Asia; its tart fruits are often used in curries or as condiment in SE Asia.

Duguetia lepidota (yara yara); Annonaceae—Amazonia (Alto Orinoco) deciduous tropical forests; sweet fruits eaten.

Elaeagnus spp. (silverberry, oleaster); Elaeagnaceae—northern hemisphere, mainly in Asia; mealy, sweetish fruits eaten locally.

Empetrum nigrum (crowberry, blackberry); Empetraceae—low–growing shrub of tundra, alpine, open boreal forest and muskeg, circumpolar; berries eaten raw, preserved by Inuit and other northern First Peoples; important emergency food.

Ficus carica and other *Ficus* spp. (figs); Moraceae—deciduous or evergreen trees of warm temperate, tropical and subtropical forests; over 1000 spp., *F. carica* one of oldest Mediterranean fruit crops, cultivated throughout Mediterranean, Middle East, U.S.; many spp. wild harvested; many species of *Ficus* are attractive crops in subtropical regions as they fruit a few times a year.

Fragaria spp. (strawberries); Rosaceae—herbaceous perennials of temperate woodlands, shorelines and clearings, Europe, Asia, N America; hybridized in Europe from two N American spp.; domesticated forms now widely cultivated in temperate regions; sweet, juicy berries widely eaten wherever they occur, fresh or in preserves.

Gaultheria shallon (salal); Ericaceae—evergreen shrub of temperate rainforest, W N America; sweet juicy berries harvested from wild by indigenous peoples, eaten raw, or cooked and dried for winter use; used to sweeten other berries.

Hippophae rhamnoides, H. salicifolia (sea buckthorn); Elaeagnaceae—large shrubs; sea and river edges, cliffs, scrub, Eurasia; acid, aromatic fruits are used for making jellies, jams and vinegar, or as an addition to sauces, in N Europe, Russia, China and Nepal.

Juniperus communis and other spp. (juniper); Cupressaceae—evergreen shrubs and trees, northern hemiphere; fleshy pseudo–fruits were eaten in small quantities by Native Americans and in Eurasia; sometimes used as spice (Germany, Italy, Poland); in northern Europe a kind of beer was brewed from them, e.g., in Poland, France, and Estonia.

Lonicera spp. (honeysuckle); Caprifoliaceae—deciduous or evergreen shrubs and vines; northern hemisphere; fleshy fruits of a few species are used as raw, as food, e.g., *Lonicera coerulea, L. angustifolia,* however most species from the genus are toxic.

(Continued on next page)

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Lonicera caprifolium (Honeysuckle); Caprifoliaceae—Europe; fruits raw, known as St. John’s grapes.

Malus fusca and related spp. (wild crabapple); Rosaceae—deciduous tree of temperate regions, moist shorelines and swampy areas to open woods, 25–30 wild species of apples and crabapples in Europe, Asia and N America; small, tart fruits harvested by First Peoples in NW N America.

Mauritia flexuosa (moriche palm, morete); Arecaceae—a palm of tropical swamps; S America; fruits important locally, e.g., for Huaorani hunter–gatherers.

Monstera deliciosa (ceriman); Araceae—evergreen vine of tropical rainforests, Mexico; distributed widely throughout tropics; cone–like fruit eaten when fully ripe.

Nephelium lappaceum and related spp. (rambutan); Sapindaceae—broad–leaved trees of tropical rainforest, SE Asia, Malaysia, Indonesia, Thailand, Philippines; around 35 species, some wild harvested.

Passiflora spp. (passionfruit, granadilla); Passifloraceae—climbing vines of tropical forests, Brazil, tropical America; many spp. with small, flavorful fruits, eaten raw, cooked or as beverage or preserves; some spp. cultivated, others harvested from wild.

Prunus virginiana, P. pensylvanica, P. avium, P. padus and other spp. (wild cherries, choke cherries); Rosaceae—deciduous trees of temperate deciduous or mixed forests, Europe, Caucasas, N Turkey, other spp. in N America, Asia; some spp. domesticated, widely grown in temperate regions as dessert fruit, some spp. harvested from wild.

Prunus spinosa and other spp. (wild plums); Rosaceae—deciduous trees of temperate deciduous forests, various spp. from Europe, N America, China; some spp. domesticated, widely grown in temperate regions as dessert fruit and for prunes and preserves, sometimes harvested from wild.

Psidium guajava (guava); Myrtaceae—broad-leaved tree of tropical and subtropical rainforests, C America; shrub or small tree; widespread as popular tropical fruit, growing wild and cultivated; used for jams and preserves; other spp. used as well.

Ribes spp. (gooseberries); Grossulariaceae—deciduous shrubs of temperate woodlands, Europe, Asia, America; various species widely grown as a soft fruit in temperate areas, eaten raw or usually cooked, preserved; many wild–harvested species.

Ribes spp. (currants); Grossulariaceae—shrubs, understorey of deciduous and boreal forests; circumboreal; fruits eaten raw or in preserves; used locally by indigenous people of N America and Eurasia, as well as in modern cuisine.

Rosa acicularis, R. canina, Rosa rugosa and related spp. (wild rose, hips); Roseaceae—deciduous shrubs of temperate regions, open woods and moist areas, W N America, with other species circumboreal, in N America, Eurasia; hips cooked into sauce, syrup, or used to make beverage tea; must be strained to remove irritating hairs from seeds; widely used as food and famine food.

Rubus chamaemorus (bakeapple, cloudberry, salmonberry); Rosaceae—low sub–shrubs of open muskeg or peat bogs of boreal forests, dioecious, circumboreal; berries harvested in quantity and sometimes marketed (Scandenavia, Newfoundland); eaten raw, cooked or preserved, and also made into a drink; rich in Vitamin C.

Rubus arcticus and related spp. (nagoonberry, lagoonberry); Rosaceae—low sub–shrubs of open muskeg or peat bogs of boreal forests, circumboreal; highly flavoured berries a favorite food of northern peoples, eaten fresh or preserved.

Rubus idaeus and other spp. (raspberries); Rosaceae—deciduous shrubs of temperate coniferous and deciduous woodlands, along creeks and rocky slopes, Europe, W Asia, N America; widely grown as a soft fruit in temperate areas; many spp. harvested from wild and eaten fresh, cooked, or preserved.

Rubus spp. subgenus *Rubus* (blackberries); Rosaceae—deciduous or evergreen shrubs of temperate and montane woodlands, Europe, Asia, N America; cultivated on limited basis; berries of many spp. harvested from wild, eaten fresh, cooked, or preserved.

Sambucus spp. (elderberries); Caprifoliaceae—deciduous shrubs and small trees of moist open woods and forest edges, widespread in N Hemisphere; small clustered, somewhat tart berries usually cooked as sauce or used for wine and other beverages.

Shepherdia canadensis (soapberry); Elaeagnaceae—deciduous shrub of open coniferous woods, across temperate N America; small somewhat bitter berries picked fresh, dried and preserved; mashed and whipped with water into a frothy confection (contains saponins), served at feasts and social occasions by NW N American First Peoples; also used to make a lemonade-like beverage.

(Continued on next page)

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Solanum spp. (ground cherry); Solanaceae—herbaceous annuals or perennials of open disturbed ground and moist clearings; many species occurring in N, C and S America; tart, juicy berries surrounded by papery sheath, eaten raw or cooked; some species under cultivation.

Solanum stramonifolium (tupirillo; paja; cocconilla); Solanaceae—Sez. *lasiocarpa*; frequent in savannas, ecotones, forest opening, and along riverbanks, tolerant the different type of soils; the fruit is eaten fresh.

Solanum sessiliflorum (cocona, tupiro, chipe chipe); Solanaceae—Sez. *lasiocarpa*; frequent in upper Amazon Basin of Colombia, Ecuador and Perù, cultivated in the "conuco" and along the Amazon and Orinoco River of Venezuela and Brazil; the fruit is eaten fresh, in vegetable salad, marmalade but the most important use is juice.

Spondias spp. (hog plum); Anacardiaceae—deciduous trees of tropical S America and Asia; several species of fruits used as food locally in both continents.

Vaccinium spp. (blueberries, huckleberries, bilberries, cranberries); Ericaceae—deciduous (or sometimes evergreen) shrubs of northern boreal and temperate coniferous and deciduous forests, Europe, N America, deciduous or sometimes evergreen shrubs; various domesticated species grown in N America, Europe, Australia, New Zealand; wild species commonly harvested and eaten fresh, cooked or dried in cakes; favorites in pies.

Vaccinium vitis–idaea (lingonberry, mountain cranberry, lowbush cranberry); Ericaceae—low evergreen shrub of boreal and montane coniferous forests, acid peat bogs and muskegs; circumpolar; cool temperate and northern regions; tart berries cooked for sauce; beverages; stored under water over winter; harvested commercially in Scandinavia.

Vaccinium caespitosum and other *Vaccinium* species (dwarf blueberry and other blueberries); Ericaceae—low, deciduous shrub of open forests and rocky mountaintops and lakeshores, temperate regions; circumpolar; berries harvested in quantity and eaten raw, cooked or dried by people throughout its range.

Vaccinium oxycoccos and related spp. (bog cranberry); Ericaceae—low creeping vines of acid peat bogs and muskegs; circumpolar; cool temperate and northern regions; tart berries cooked for sauce; beverages; stored under water over winter.

Viburnum edule and related spp. (highbush cranberry); Caprifoliaceae—deciduous shrubs of moist forests, lake edges and creeks; circumpolar; tart berries cooked and eaten, considered high value feast and trade food, often eaten with grease by First Peoples; also emergency food, remaining on the bushes overwinter.

Grains, seeds and nuts

Amaranthus spp. (amaranth); Amaranthaceae—disturbed ground, moist clearings; widespread in many parts of the world; seeds eaten as parched or ground "grain", rich in protein (greens also eaten); some cultivated spp.

Araucaria araucana and *A. angustifolia* (araucaria, monkeypuzzle); Araucariaceae—evergreen trees of S temperate coniferous forest, two spp. in Chile, Brazil, Australia, evergreen trees; seed kernels eaten locally by indigenous peoples.

Bertholletia excelsa (Brazil nut); Lecythidaceae—large, broad–leaved trees of tropical rainforest, Amazonia, S America; thick–shelled, oily nuts harvested wild from Brazil and other S American countries; most exported to U.S. and Europe.

Carum carvi (Caraway); Apiaceae—Europe; arable land; leaves boiled in the spring mixture; plant included in the "pistic" blend; shoots, achenes and sprouts raw as spices in salads or cooked in the spring blend.

Carya illinoensis and related spp. (pecan, hickory nuts); Juglandaceae—deciduous trees of temperate and warm hardwood forests, E and SE United States and Mexico; nuts eaten by First Peoples; now pecan is a major wild and plantation crop; also grown in Australia, Brazil, S Africa.

Castanea sativa and other spp. (chestnut); Fagaceae—deciduous trees of Mediterranean and temperate hardwood forests, S Europe, Turkey; other spp. in E North America, E Asia, deciduous tree; domesticated and grown in S Europe, also harvested from wild growing trees; nuts contains starch and high quality protein; eaten as flour, bread, porridge, sweetmeats.

Corylus spp. (filbert, or hazelnut); Betulaceae—deciduous tall shrubs of temperate forests, Asia Minor, SE Europe, N America; cultivated in England and North America, also wild harvested for millennia; nuts used in baking and confections.

Fagus grandifolia, F. sylvatica (beechnut); Fagaceae—deciduous trees of temperate forests, E N America, Europe; nuts gathered from the wild and eaten locally, raw or roasted.

Foeniculum vulgare (fennel); Apiaceae—leaves and stems eaten raw or cooked, seeds are used as a flavoring in castagnaccio cakes; traditionally collected in Ligurian region.

Glyceria fluitans (water mannagrass); Poaceae—herbaceous perennial, water margins; mainly in Europe; grains gathered in eastern Europe (mainly in Poland) to make highly valued and expensive bread.

(Continued on next page)

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Juglans (walnut); Juglandaceae—trees, decidous temperate and subtropical forests of northern hemisphere; kernels of nuts are valued food in many parts of the world.

Mentzelia albicaulis (white–stemmed blazing star); Loasaceae—herbaceous flowering plants of drylands in W N America; seeds gathered, parched and eaten by Indigenous peoples of the Great Basin and California.

Myrrhis odorata (Sweet Cicely); Asteraceae - seeds and young leaves used as spices, elixir, in salads and soups.

Pinus pinea, P. sibirica, P. edulis, P. cembra, P. koraensis and other spp. (pine nuts); Pinaceae—evergreen coniferous trees of various species in dryland temperate and sub–boreal coniferous forests, various species native to SW United States, Europe, Asia, Russia, evergreen trees; seeds high fat, high–protein, eaten by many groups of Indigenous Peoples; eaten and exported worldwide as specialty foods.

Quercus spp. (oak/acorns); Fagaceae—deciduous or evergreen trees of temperate dryland forests of Europe, Asia, N and C America; acorns eaten in large quantities by N American indigenous peoples; usually pounded into meal and leached to remove tannins before consuming; widely used in Eurasia as famine food.

Trapa natans, T. bicornis etc. (water caltrop); Trapaceae—annual plants of lakes and ditches; warmer temperate and subtropical parts of Eurasia; fruits important part of human nutrition throughout Europe in prehistoric times; still widely eaten in Asia.

Other edible plants and plant substances, mushrooms, lichens, and algae

Acacia senegal and other spp. (gum arabic); Fabaceae—deciduous trees of dry tropical forest/ savanna, W Africa; other spp. found in arid regions of all continents, wild and plantation harvested gum used in food industry for texture, stabilizer in confections, beverages; also in cosmetics, medicinal products.

Acer saccharum and other spp. (sugar maple); Aceraceae—deciduous trees of temperate hardwood forest, SE Canada, NE United States; sap harvested in quantity and rendered into syrup and sugar; commercial product.

Aniba rosaeodora (bois de rose); Lauraceae—tropical rainforest, Amazonia, Brazil, Peru; essential oil distilled from bark and fruit, used as flavor ingredient in many processed foods and beverages.

Arenga pinnata and other spp. (sugar or gomuti palm); Arecaceae—tree palm of tropical forests, Annam, SE Asia, Philippines; wild and plantation trees yield sap, rendered into sugar.

Armillariella spp. (honey fungus); Marasmiaceae—a brownish parasitic fungus, fruiting bodies appear in large groups on dead wood, circumboreal; eaten in boiled or pickled dishes, mainly in Slavic countries, also in China.

Armoracia rusticana (horseradish); Brassicaceae—pungent root used as a condiment for meat and other dishes in Europe.

Betula spp. (birch); Betulaceae—tree of temperate forests, circumpolar; sap collected in spring, drunk raw, fermented or concentrated; used, e.g., in Alaska, Russia, Ukraine.

Boletus edulis and other spp. (edible bolete, or cep); Boletaceae—mushrooms of temperate deciduous and coniferous forest, throughout northern hemisphere; especially E Europe, also S America in pine plantations; highly valued and widely gathered, especially in Poland and E Europe, and Italy.

Cantharellus cibarius and other spp. (chanterelles); Cantharellaceae—mushrooms of temperate coniferous forest, throughout northern hemisphere; highly valued and widely gathered; large quantities exported from British Columbia and US Pacific NW.

Caryota urens (fishtail palm); Arecaceae—a monocarpous palm, subtropical forests; India to Malay Peninsula; starchy pith used to make flour; sap made into sugar.

Eugeissona utilis and other spp. (sago palms); Arecaceae; — palms from tropical forests; Borneo and Malay Peninsula; the starchy pith is the staple food of Penan hunter–gatherers in Borneo.

Gaultheria procumbens (wintergreen); Ericaceae—low evergreen shrub of temperate deciduous forest, E N America; leaves, berries used as flavoring for tea, candy, gums, toothpaste.

Ilex paraguariensis (yerba maté); Aquifoliaceae—small evergreen tree of tropical forests, S America, primarily Paraguay, Uruguay, S Brazil, Argentina; leaves a popular, caffeine–containing S American beverage; used medicinally as stimulant for fatigue, depression, pains.

Juniperus communis and other spp. (junipers); Cupressaceae—low, evergreen coniferous shrub to small tree, temperate and boreal coniferous forests, northern hemisphere; “berries” used as flavoring for gin and meat dishes; in Poland fermented into beer.

Lactarius deliciosus s.l. (saffron milk cap); Russulaceae—orange mushrooms growing under conifers in Eurasia and Africa; used in the traditional cuisine of E Europe, N Africa, Spain, France and parts of China.

Ledum spp. (syn. *Rhododendron* spp.) (Labrador–tea, trapper’s tea); Ericaceae—evergreen broad–leaved shrub of acidic peat bogs and muskeg, circumpolar; leaves harvested and used as beverage tea widely across boreal and temperate N America.

(Continued on next page)

TABLE 1

Edible Wild-Growing Plants (and Algae, Fungi, Lichens) of the World; selected examples (after Cappelletti *et al.*, 2000; Crowe, 1981; Hedrick, 1992; Hu, 2005; Kuhnlein and Turner, 1991; Maurizio, 1927; Paoletti *et al.*, 1995, Paoletti, 2004; Tanaka 1976; Turner, 1995, 1997). *(Continued)*

Leptospermum scoparium (manuka, or tea tree); Myrta acea shrubs or tall trees of New Zealand forests; sugary gum eaten by Maori and highly regards; leaves used as a tea, similar to green tea.

Manilkara zapota (chicle, sapodilla); Sapotaceae—broad–leaved tree of tropical forests, Mexico, C America; latex from wild trees used as gum base in chewing gum.

Mentha arvensis and related spp. (wild mints); Lamiaceae—herbaceous perennials of temperate regions, moist prairies and slopes; leaves widely used as beverages and flavorings.

Morchella spp. (morels); Morchellaceae—mushrooms of temperate deciduous and coniferous forest, throughout northern hemisphere; also *Australcedrus chilensis* forests of Argentine, Chile; highly valued and widely gathered and exported as specialty food.

Parkia speciosa, P. africana; Fabaceae—both green and mature seeds and the fleshy pulp surrounding them are used in various vegetable dishes in S, SE Asia and parts of Africa.

Picea glauca, P. mariana and related spp. (spruce); Pinaceae—evergreen trees of N temperate and boreal regions; hard old sap/pitch chewed like gum, boughs used for beverage, rich in Vitamin C.

Pinus spp. (pines); Pinaceae—evergreen coniferous trees of N temperate regions, Mediterranean, Middle East; inner bark removed in spring and eaten by many local and Indigenous peoples in the past.

Pleurotus ostreatus and other spp. (oyster mushrooms); Pleurotaceae—mushroom growing on living and rotting wood in temperate deciduous and coniferous forest, throughout northern hemisphere; highly valued and widely gathered and exported as specialty food, also cultured.

Phoenix sylvestris (wild date palm); Arecaceae—palm tree of tropical forests, India; sap rendered into sugar.

Polypodium glycyrrhiza (licorice fern); Polypodiaceae—small patch–forming fern of rocky outcrops and tree trunks, W N America; rhizomes used as sweetener and flavouring by Indigenous peoples.

Prosopis glandulosa (honey mesquite); Fabaceae—tall shrub of desert regions; SW N America and N Mexico; pods harvested, pounded into meal and eaten (seeds actually discarded).

Sassafras albidum (sassafras); Sassafrasaceae—deciduous tree of temperate hardwood forest, E N America; bark from wild trees long used as flavoring for soups and confections and as beverage tea.

Tricholoma matsutake, T. magnivelare (pine mushrooms, matsutake); Tricholomataceae—mushrooms of temperate coniferous forests, various spp. throughout northern hemisphere, prized especially in Japan; large quantities exported from NW N America to Asia.

Tuber melanosporum, T. aestivum and other spp. (truffles)—subterranean fungi of deciduous woodlands, especially beech woods, France, Italy, U.K.; high value food and condiment in European (especially Italian and French) cuisine.

Wasabia japonica (wasabi); Brassicaceae—pungent root of this and related spp. used as a condiment in Japan and Korea.

Flowers

Bassia latifolia (mohua); Sapotaceae—a tree, E India; the succulent flowers fall by night in large quantities from the tree, are gathered early in the morning, dried in the sun and sold in the bazaars as an important article of food; also important food of Chenchu hunter–gatherers.

Centaurea cyanus (cornflower); Asteraceae—Europe; flowers raw or cooked.

Sambucus nigra (black elder); Caprifoliaceae—a large shrub; deciduous temperate forests of Eurasia; flowers used to make cordials, syrups, wines, or fried in batter in many European countries.

Hemerocallis (day lily); Liliaceae—perennials, grasslands and rocky outcrops, mainly in Asia; fleshy flower petals of many species used raw or dried as a vegetable in E Asian cuisine, most commonly in China.

Taraxacum officinale (dandelion); Asteraceae—perennial of Eurasian origin, now cosmopolitan in meadows and lawns, in Poland flowers are boiled with sugar to produce honey-like substance.

Sesbania grandiflora; Fabaceae—a small tree, SE Asia, flowers widely used as a vegetable.

Polygonum tubers were also known as an emergency food in Scandinavia, Switzerland and Germany (Eidlitz, 1969). *Polygonum* species have a particularly high vitamin C and carotene content. For example, *P. bistorta* has 158 mg vitamin C per 100 g fresh weight (Kuhnlein and Turner, 1991). Other major root vegetables, many of them still being used but to a lesser extent than in the past, include certain ferns (e.g., *Dryopteris expansa*, wood fern), and flowering plants in the arum family

(Araceae), sedge family (Cyperaceae), lily family (Liliaceae), cattail family (Typhaceae), celery family (Apiaceae), aster family (Asteraceae), legume family (Fabaceae), purslane family (Portulacaceae) and nightshade family (Solanaceae), among many others. Some of these families (e.g., Liliaceae, Apiaceae, Solanaceae) also contain highly toxic metabolites and some need special preparation to render them edible (cf. Johns and Kubo, 1988). People harvesting wild roots (and any wild growing species) for food need to be extremely careful in identifying and preparing them (Turner and Von Aderkas, 2009). There is yet another concern about harvesting underground organs of wild plants from natural ecosystems: some of them are slow growing species (e.g., *Corydalis, Lilium, Erythronium, Polygonatum*) growing in high competition environments and harvesting larger amounts may endanger local populations.

As major storage organs of plants, root vegetables typically contain carbohydrates that are usually at their highest density at the end of the leaf-growing season, before new shoots appear. Carbohydrates can be present in a variety of forms and flavors, and may not always be readily digestible for humans. Some traditional root vegetables, like camas bulbs (*Camassia* spp.) and onions (*Allium* spp.) in Liliaceae, and balsamroot (*Balsamorhiza sagittata*) and thistles (*Cirsium* spp.) in Asteraceae, contain large proportions of inulin, a complex carbohydrate that becomes sweet upon cooking due to a partial conversion to the sugar fructose. Some of these species are traditionally cooked in underground pits, or earth ovens, flavored with various types of plants that also apparently enhance their conversion to fructose and fructans (Peacock, 1998; Konlande and Robson, 1972). Many other root vegetables can also be pit-cooked, and this is an excellent method of preparing them for a feast or for drying for storage. If the skin of root vegetables is consumed, it can be a good source of mineral nutrients. Usually, root vegetables provide only small amounts of vitamins in a 100-gram portion. They are typically eaten with fish, meat or fat of some type (Kuhnlein and Turner, 1991).

B. Edible Greens (Leaves, Stems, Shoots, Including Marine Algae)

Hundreds of different wild plant species produce tender, edible shoots and leaves, especially in the spring or at the beginning of their growing season. Potentially a high percentage of a flora yields edible greens. Out of Polish vascular plant flora (3,000 species) at least a third was used as wild greens in some country of the world. Some, like thimbleberry and its relatives (*Rubus parviflorus, Rubus* spp.) and cow-parsnip (*Heracleum maximum*), can be eaten raw, after being peeled, whereas others, like stinging nettles (*Urtica dioica*), must be steamed or cooked in some way. Many green shoots, such as fireweed (*Chamerion angustifolium*) and horsetails (*Equisetum* spp.), as well as those mentioned previously, grow from branching rhizomes and form extensive patches. They can often be harvested several times over a season, in a manner similar to asparagus (*Asparagus officinalis*—which also has wild-harvested relatives). Other types of leafy edible greens, like lambsquarters (*Chenopodium* spp.), amaranths (*Amaranthus* spp.), purslane (*Portulaca oleracea*) and mustards (*Brassica* spp., *Sisymbrium* spp. and others), are weedy annuals, often growing in disturbed ground. In Mediterranean Italy several assemblages of especially spring tender leaves are collected under collective names such as ***pistic*** or ***litum***, ***frita*** in Northeastern Italy (Paoletti *et al.*,1995; Dreon and Paoletti, 2009) or ***prebuggiun or preboggion***) in Liguria (Bisio and Minuto, 1997, 1999).

In the Southwest United States and Central America (as well as in other places), these weedy greens, called ***quelites***, are left growing amongst cultivated crops like maize and squash, providing the farmers with a greater variety of food from the same site, and thus a wider range of nutrients. (Bye, 1981) Most edible wild greens have high moisture content, and contain carotene and other vitamins (vitamin C and folic acid) and minerals such as iron, calcium, magnesium, are also high in antioxidants, etc. (Kuhnlein and Turner, 1991; Sacchetti *et al*., 2009).

Marine algae, or seaweeds (now considered to be in their own kingdom, but included here with edible greens), have been used by virtually all coastal peoples, and are sometimes traded to interior regions. Still widely used at present in many parts of the world, they are rich sources of vitamins and several minerals, particularly iodine. Some algal species can be difficult to digest unless specially processed. A few species, like Japanese ***nori*** (*Porphyra* spp.), have been domesticated and are produced commercially, but in most cases, people are still using wild-growing species (Turner, 2003). As with the root vegetables, some edible wild greens have toxic look-alikes, and people have been seriously poisoned, for example, by mistaking the highly poisonous false hellebore (*Veratrum viride*) for the edible shoots of false Solomon's-seal (*Maianthemum racemosum*) (Turner and Von Aderkas, 2009). Many edible greens are particularly important for their vitamin C content in the spring, and can be used to prevent and alleviate scurvy.

C. Berries and Other Fleshy Fruits

Wild berries and other fleshy fruits (including drupes, pomes, and aggregate fruits) are perhaps the most favored group of edible wild plants, and probably the most frequently used today, at least by contemporary Indigenous people of Canada (Kuhnlein and Turner, 1991). They include very sweet and juicy species like wild strawberries (*Fragaria* spp.), Saskatoon berries (*Amelanchier alnifolia*), blueberries and huckleberries (*Vaccinium* spp.), salal berries (*Gaultheria shallon*), blackberries and raspberries and their relatives (*Rubus* spp.). Other types are more tart, but nevertheless flavorful: crabapples (*Malus* spp.), wild cherries and plums (*Prunus* spp.), gooseberries and currants (*Ribes* spp.), lingonberries (*Vaccinium vitis-idaea*), bog cranberries (*Vaccinium oxycoccos* and related species), and highbush cranberries (*Viburnum* spp.). Many of these are the wild ancestors of diverse cultivated fruits, and some, like lingonberry and cloudberry, or bakeapple (*Rubus chamaemorus*) from the boreal forests and muskegs, are used commercially as wild-harvested species. Some fruits, like kinnikinnick berries (*Arctostaphylos uva-ursi*), rose hips (*Rosa* spp.), and crowberries (*Empetrum nigrum*) are little eaten today, but are still important in some situations, such as for those stranded in remote areas in the wintertime, since they remain on the plants over the winter. One very special wild fruit for Indigenous Peoples in western North America is called soapberry (*Shepherdia canadensis*; Elaeagnaceae). It contains small amounts of saponin, a natural detergent, and can be whipped with water and a bit of sweetener into a frothy confection resembling whipped egg whites, and is still eaten today as a special treat (Turner and Burton, 2010). Most wild fruits are good sources of ascorbic acid (Vitamin C); some, such as rose hips, are exceptionally high in this important nutrient. Cranberries and wild blueberries are now recognized for their antioxidant flavonoids, which have therapeutic properties and are used as nutriceuticals (McCune, 1999). Fruits can also contain unexpectedly high amounts of other nutrients such as calcium, vitamin A as carotene, and folic acid (Kuhnlein and Turner, 1991).

D. Grains, Seeds, and Nuts

Edible wild seeds, nuts and grains include wild-rice (*Zizania aquatica* and related spp.), amaranth (*Amaranthus* spp.), oak acorns (*Quercus* spp.), hazelnuts (*Corylus* spp.), black walnuts (*Juglans nigra*), hickory nuts (*Carya* spp.), wild sunflower (*Helianthus* spp.) and pine seeds (*Pinus* spp.), among numerous other species. Some types, like acorns, must be thoroughly processed by leaching and cooking to remove bitter-tasting tannins before they are edible. (Some species of oaks, such as the "white oak" group, have acorns with much lower levels of tannins.) Nuts have hard outer shells that must be cracked off to extract the edible kernels. Some also have spiny or prickly husks that have to be removed. In the past, people have sought nuts and seeds, already dehusked, from the caches of small mammals.

Wild grains, the one-seeded fruits of grasses (Poaceae), are similar in their nutritional properties to many domesticated types. (The grass family includes some of our most important worldwide economic plants, such as wheat, barley, rye, maize, rice, and other cereal grains, bamboo, and sugar cane.) After harvesting, grains usually require threshing to remove their outer covering, or chaff, and then the kernels can be parched and ground into an energy-rich meal. Many different peoples have harvested and sometimes tended wild grasses for their grains. For example, sea lyme grass, or strand-wheat *(Elymus arenarius*) was a cereal grain of the Vikings. Its carbonized grains occur in Viking archaeological sites of Iceland and Greenland, and it was introduced long ago by Vikings to Newfoundland in eastern Canada. The Timbisha Shoshone of the American Great Basin, as well as the Kumeyaay of California and other Indigenous Peoples, sometimes broadcast grains of rice-grass (*Achnatherum hymenoides*; syn. *Oryzopsis*) and other grass species in recently inundated river edges or moist hollows, and also occasionally burned over grasslands to maintain open habitats for grasses and other prairie species (Fowler, 2000). Other wild grass species used for their grains include blue grama (*Bouteloua gracilis*), Canada wild rye (*Elymus canadensis*), June grass (*Koeleria cristata*), muhly (*Muhlenbergia* spp.), panic grass (*Panicum* spp.), and sand drop-seed (*Sporobolus cryptandrus*) (Kindscher, 1987).

Wild-rice is probably the best known wild-harvested grain in North America. Along with sunflower (*Helianthus annuus*) it is one of the truly North American grains that has gained commercial importance in world markets. It has been harvested by many Indigenous Peoples of eastern North America since prehistoric times. One group, the Menominee, is named after this grain, which is called "***menoomin.***" Some people traditionally sowed the wild-rice, whereas others let it seed itself naturally. It grows in standing water along the edges of quiet rivers and lakes. The grains are harvested from the water, with people—usually women—hitting the fruiting heads with a stick to knock the grains off into the bottom of the canoe. The harvested grain is dried on mats or over a fire, the hulls thrashed off by trampling, then the hulled grains winnowed by tossing them on a tray in the breeze or by fanning them, to separate out the chaff. The grain can then be stored in sacks or underground caches for future use, or for trade or sale. Wild-rice can be prepared and served in many different ways. Often it was cooked in soups, or boiled with meat, fish, roe, or with blueberries or other fruits. One favorite dish is wild-rice, corn, and fish boiled together. The cooked grain can also be eaten plain, boiled or steamed, and eaten with sweets such as maple sugar (Jenks, 1977; Kuhnlein and Turner, 1991; Nabhan, 1989). Wild-rice is now being marketed by some Indigenous groups, such as the Anishenaabe (Ojibwa), and has been made famous as a Slow Food Presidium product through the work of Anishinaabe activist Winona Laduke, founding director of the White Earth Land Recovery Project in Minnesota, USA (http://nativeharvest.com/).

Nuts, seeds, and grains are generally known to be good sources of protein, fat, carbohydrates, vitamins, and minerals. In some cases, oil can be rendered from various seeds and nuts, making them particularly good energy sources. Nuts are also good sources of minerals, such as iron, the B-vitamins, and amino acids. Cooking tends to enhance their digestibility and nutrient availability.

E. Other Edible Plants, Mushrooms, Lichens, and Algae

Other wild species used as food include dozens of marine algae, numerous edible fungi, a few species of lichens, the inner bark, cambium and liquid sap of trees, including the famous sugar maple (*Acer saccharum* and other spp.). Few studies have been done on the nutrient content of wild mushrooms, but wild species are probably comparable in their nutrients to commercially available types (Kuhnlein and Turner, 1991). They contain small amounts of sugar and large amounts of microelements.

The mushrooms of the family Boletaceae, commonly harvested in many countries, contain proportionally high amounts of protein. Among the best known wild-harvested fungi are truffles (*Tuber melanosporum, T. aestivum* and other spp.), which are a high-value food and condiment, especially associated with French and Italian cuisine. These subterranean spore-bearing organs are sought by specially trained dogs, or sometimes pigs, from the beech and other forests of several European countries. In Japan, matsutake (*Tricholoma matsutake*) and its North American counterpart, *T. magnivelare*, are similarly highly valued fungi, mainly of conifer forests, whose harvest is both commercial and a culturally valued activity. Many people, especially in parts of Europe, Russia and North America, enjoy harvesting wild mushrooms like chanterelles (*Cantharellus*) and morels (*Morchella*) as a recreational activity.

Edible inner bark tissues include those of conifers like hemlock (*Tsuga* spp.), spruce (*Picea* spp.), firs (*Abies* spp.) and pines (*Pinus* spp.), as well as cottonwood (*Populus balsamifera*), alders (*Alnus* spp.) and other deciduous trees (Turner *et al.*, 2010). These tissues were harvested by removing patches of bark from living trees, usually in the springtime, and scraping the edible tissue from the inside of the bark or the outside of the wood. There is little documentation of nutrient content of these foods, but many are sweet tasting, and probably have a high sap content, and therefore high energy values in the form of sugars.

Many plants are also used to make beverage teas. Some of these, like Labrador tea (*Ledum palustre* and related spp.; Ericaceae), field mint (*Mentha arvensis*; Lamiaceae) and yerba buena (*Satureja douglasii*; Lamiaceae), are highly aromatic. Teas from plants are often taken as medicines or tonics as well as regular beverages. Many aromatic plants are also used to sweeten or to flavour other beverages and foods during processing or cooking. For example, salal leaves (*Gaultheria shallon*) are used in pit-cooking root vegetables in western North America (Turner, 1995). Several species of the mint family (Lamiaceae) are used as culinary herbs in soups and stews, as are some species of the celery family (Apiaceae) such as Indian celery (*Lomatium nudicaule*) greens and seeds. Some of these plants, as well as some aromatic plants in the aster family (Asteraceae; e.g., *Artemisia* spp.), have also functioned as preservatives for meat and fish. Flower petals and nectars are sometimes sought, especially by children, and people also chew the gums or resins of a number of different trees for pleasure. Flowers are high moisture-containing foods, usually low in protein and fat, but some can be remarkably rich in vitamin A as carotene or vitamin C.

III. TENDING AND MANAGING WILD PLANTS

Many edible wild plants are "pioneer" species, well adapted to disturbance from forest fires, floods, soil disruption and browsing by animals. Ancient humans, as well as our Neanderthal and primate relatives, must have observed the enhanced growth of leafy plants in floodplains or wetlands, the high productivity of berry bushes and strawberries following forest fires (Boyd, 1999; Paoletti *et al*., 2007), or the ability of wild fruit trees and bushes to produce more fruit in succeeding years when their branches are broken back. Studying the habits of bears, monkeys and other animals must have been especially helpful for humans learning about edible species—how to harvest them, and how their productivity and quality could be promoted through small-scale disturbance. In fact, some of the earliest human foods are the same as those sought by other omnivores: inner bark of trees, various types of greens, starchy roots, seeds and grains, and sweet-tasting, juicy fruits. Furthermore, humans may have developed methods of storing seeds, nuts, roots and fruits based on watching squirrels and other rodents, as well as various birds, caching their winter food supplies. Humans have learned to exploit some of these animal caches to obtain ready-harvested food.

The knowledge that Indigenous peoples and others long-resident in particular places have acquired and developed about their environments and ways of using their resources sustainably is part of a complex system, commonly termed "Traditional Ecological Knowledge." Traditional Ecological Knowledge, or TEK, is defined as "A cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes, 2008). This knowledge system incorporates, for many peoples, practical knowledge relating to sustainable use of plant resources, including edible wild species. This practical knowledge is embedded in particular worldviews or belief systems that often place humans *within* (rather than superior to) other species, and therefore foster greater care for other species. For example in harvesting bark from trees, people are often careful to harvest bark only partially around the trunk so as not to kill the tree, since it is seen not just as a resource, but as a living being, to be respected and preserved if at all possible (Turner *et al*., 2009). The first berries and greens of the season are sometimes recognized and celebrated with a "First Foods" ceremony and a feast, such as the special ceremony for the black huckleberries (*Vaccinium membranaceum*) held by the Okanagan and other Indigenous Peoples of the Interior Plateau of western North America. Traditional Ecological Knowledge systems also incorporate means of communicating and transmitting environmental knowledge including information on the harvesting, processing and sustainable use of edible plants, their seasons and cycles of production, their habitats and their use by other species.

People have developed many different strategies for maintaining and enhancing these foods (Anderson, 2005; Deur and Turner, 2005). Some of these techniques include: clearing and burning areas to create more open and patchy environments to promote a higher diversity and greater productivity of key species, such as with camas (*Camassia* spp.), huckleberries (*Vaccinium* spp.) and wild raspberries and their relatives (*Rubus* spp.); partial and selective harvesting, especially of inner bark of trees, root vegetables and wild greens; pruning and coppicing (cutting back to the ground level) of certain species like oaks (*Quercus* spp.), blueberries (*Vaccinium* spp.), salmonberries (*Rubus spectabilis*) and hazelnuts (*Corylus* spp.); fertilizing and mulching with various organic remains; and habitat modification, such as digging, weeding, thinning and replanting in the traditional root gardens of the estuarine tidal marshes along the Northwest Coast of North America (to produce larger quantities of northern riceroot (*Fritillaria camschatcensis*), silverweed (*Argentina egedii*) and springbank clover (*Trifolium wormskjoldii*); and focused ownership and stewardship of productive patches (Balée, 1994; Dear and Turner, 2005; Turner *et al*., 2005; Turner *et al*., 2009). Seedlings of wild fruit trees are often left in field margins or specially protected in the forest. For example in the Carpathians, wild cherry (*Prunus avium*) trees were often spared from cutting for fuel and left in at the edges of fields where other species of trees were not allowed to grow (Marciniak, 2008). In lowland Poland wild pears (*Pyrus pyraster*) had a similar role, as did Pacific crabapple trees on the Northwest Coast of North America (Turner and Peacock, 2005). In the Amazon several wild plants are protected and their dissemination facilitated by spitting the seeds of fruits along the tracks in the forest, increasing the probability of the dissemination of selected fruit plants such as *Paurouma cercopifolia* or *Duguetia lepidota* (Paoletti, 2004) in places accessible to villagers.

The end result of these practices is an entire set of different edible plant species that can be considered partially domesticated (semi-domesticated), or at least that live in habitats that are tended, or domesticated: "*ethnoecosystems*." One could argue that such habitats are simply a stage in a "progression" to domestication and more intensive agriculture, yet many of these ethnoecosystems have remained in place as stable and productive systems for thousands of years, and are best regarded simply as another form of cultivation in a wide range of different practices and strategies of food production (Deur and Turner, 2005).

Many Indigenous and local peoples around the world still harvest and depend upon edible wild species (Kuhnlein *et al*., 2009, in press). However, even in relatively remote regions like the Canadian Arctic, indigenous dietary constituents are being displaced with marketed foods. Research is showing that diets of highly processed foods, with excessive refined carbohydrates and saturated fats are not healthy; combined with changes in peoples' lifestyles, they are leading to high rates of obesity, diabetes, and heart disease, particularly in Indigenous populations (Kuhnlein *et al*., 2009).

Some may think that wild-growing foods are no longer relevant for modern humans. However, there are many reasons why we need to retain the rich knowledge of the food systems of Indigenous peoples and of those who were the ancestors of all of us. Furthermore, many locally growing foods are central to people's cultures and cultural identity and in these cases their use is essential for spiritual and emotional, as well as physical health. Harvesting and preparing wild foods can bring tremendous pleasure to any group of people, for example, in family harvesting expeditions for wild berries, mushrooms or edible seaweeds. Extra harvests can be preserved and stored for later use, to be shared at family gatherings or as gifts. These wild foods also provide dietary diversity, which is important for good nutrition (Kuhnlein *et al*., 2006; 2009; in press). Furthermore, at times of emergency, such as for hikers or others stranded in remote places without access to other food, wild foods can still save lives. Wild species also serve as fundamental sources for genetic research and the development of new domesticated crops.

Perhaps most importantly, continued knowledge and use of edible wild species keeps us connected to our environments, and therefore promotes ecological awareness and ecological integrity. Ethnoecosystems are generally high in biological diversity, and serve as indicators for a healthy environment, with intact, diverse and resilient relationships between humans and other species. They contribute to both ecological and social sustainability. In short, understanding the ways in which indigenous and local peoples manage, maintain and enhance many wild-growing species, working with natural processes and natural interconnections (Senos *et al*., 2006), can help all of us to sustain and restore our critically important environments and habitats.

IV. WILD FOOD PLANTS IN DIFFERENT ECOSYSTEMS

Main types of food plants (e.g., those yielding edible leaves, fruits, or starchy underground parts) can be found in all types of ecosystems. However, the proportions across edible lifeforms are different. Temperate deciduous forests and steppes yield large quantities of succulent green shoots in spring, whereas in arid ecosystems plants to protect themselves from herbivores a greater extent by producing alkaloids and other chemical deterrents and such armour as prickles and thorns. Thus, even in a rainy season they are likely to be less palatable than species growing in ecosystems with more rainfall. In southern Europe, many bitter-tasting Asteraceae species have been eaten in rural communities (e.g., *Leontodon, Cichorium, Hypochaeris, Sonchus*), whereas these same species were usually passed by as edible plants further north in Europe, where there was usually a sufficient supply of less bitter green shoots and leaves of plants (e.g., *Urtica*, *Chenopodium*, *Aegopodium*) to be found in the grasslands and fields. This difference in use of bitter tasting plants may represent a cultural choice, but the primary underlying reason for variation may be the availability of green shoots in a particular landscape.

In the tropics, although there is enough moisture, the leaves of most plants are large, hard, and waxy. In Amazon, leaves of plants play a minor role in human nutrition, whereas in Southeast Asia many different green vegetables are utilized. However these are mainly of plants growing in disturbed sites or wetlands, as these species generally have more delicate, succulent leaves. Actually, the utilization of aquatic plants has yet another advantage: many genera of aquatic plants (e.g., *Typha, Sagittaria, Schoenoplectus*) have very broad geographical ranges.

Plants with parts high in carbohydrates are particularly important in the history of human nutrition. A major source of food energy, they have been vital for survival of many hunter-gatherer groups, just as they are for agrarian peoples. Underground storage organs such as true roots, bulbs, rhizomes and tubers that are rich in starch or inulin should be mentioned at the outset. They are particularly abundant in biota displaying strong seasonal dynamics, e.g., savannah, steppes, and temperate forests. Thus, underground storage organs have been important staples for many peoples of North America, Siberia, and Central Asia, as well as hunter-gatherers of the Kalahari. In tropical forests where little biomass is stored underground the starch-rich staples generally occur above ground, for example in the pith of palms and cycads. "The heart of the palm" and sago are among the most important plant staples for forest-dwellers of the tropics. As with green shoots, aquatic ecosystems yield underground starchy organs everywhere in the world, and such genera as *Typha, Nuphar, Nymphaea, Trapa, Scirpus, Schoenoplectus, Nelumbo* and/or *Sagittaria* have been widely utilized across different climatic zones. Their ubiquity may have made aquatic and marsh plants a particularly attractive kind of wild food. For foraging bands arriving from a different area, these plants would have represented a reservoir of already recognized food. Aquatic ecosystems are also most productive. Harvesting aquatic plants may thus be more efficient than harvesting from other ecosystems (Szymański, 2008), ultimately enhancing the importance of these species. One of the most productive wild food plants is cattail or bulrush (*Typha*). *Typha* species were utilized by such broad spectra of cultures as: Native North Americans, Indigenous peoples of Siberia, Chinese, Thai, Cossacks, Egyptians, and the Tuaregs of the Sahara. The starchy rhizomes of waterlilies from the family Nymphaeaceae were also an important source of nutrition, at least in times of famine, for Native Americans, inhabitants of Polesie region between Belarus and Ukraine, and Australian Aborigines (Hedrick, 1972).

Plants yielding dry fruits and seeds were relatively more important in traditional economies than fleshy fruits. They were easier to store and contain larger amounts of fats, proteins and starch, as compared with the higher quantities of simple sugars in fleshy fruits. Thus, seeds and nuts were a more "filling source" of food, allowing them to become staples, rather than snacks, additives or famine foods. Dry fruits and seeds capable of sustaining human populations can be found in various biomes: dry and wet, hot and cold. Specialized Indigenous economies evolved around utilizing the most productive of these seeds, e.g., *Zizania aquatica*, *Quercus* spp., *Pinus* spp., *Carya* spp. in North America, *Trapa natans* in prehistoric Europe, and *Corylus* spp. in both "Old" and "New" Worlds.

The use of many of these wild foods, as noted earlier, has declined dramatically in many parts of the world. Is it possible to go back to gathering some of these wild-harvested foods that were so important to peoples of the past? In theory, yes. But their productivity is usually a fraction of that of modern crops, and many of the habitats where they once occurred in abundance have been eroded by urban and industrial development. Thus, special consideration should be taken concerning, for example, their conservation. Wild plants also generally have higher concentrations of alkaloids and other plant metabolism products, which make them good candidates as "nutriceuticals," to be eaten in small amounts as herbal medicines. In the Mediterranean region the wild collected plants have a very high antioxidant content making them an important defense against cancer and cardiovascular diseases (Vanzani *et al*., 2010, Sacchetti *et al.*, 2009). However, these same phytochemicals may pose hazards to health when larger amounts are consumed (Turner and Von Aderkas, 2009).

In the history of human science there have been many scholars who tried to popularize the use of "new crops" of wild origin. Undernourishment has been a universal phenomenon right up to the present day, and many attempts have been made to alleviate it. As Maurizio (1927) reports, German and Austrian authorities organized large-scale wild food plant collection schemes during World War I. Even soldiers were fed *Typha* products. However, after the war the population reverted to "normal" nutrition. This attitude can be explained by the so-called *optimum foraging model.* A given population uses a resource which is most nutritious and common. Once this resource becomes scarcer the people switch to the next in terms of harvesting opportunities and caloric efficiency. In North America large tracts of deciduous forests are used for sugar maple production, mainly from *Acer saccharum*. In Europe the utilization of tree sap has been recorded in most countries and in the Austro-Hungarian Empire attempts were even made to produce sugar on an industrial scale from European maple species (probably mainly *Acer pseudoplatanus*). However these efforts were abandoned. Why? Probably this was due to a few factors working together. In North America sugar maple is a dominant species in many areas, whereas in European forests maples usually form only an admixture. Secondly, the sugar content in maples other than *Acer saccharum* is generally lower. Thirdly, Europe is a densely populated continent, and fuel wood has a higher value than in more sparsely populated America. For all of these reasons, commercial maple sugar and maple syrup production in Europe has not been successful.

A. Basic Patterns of Utilization of Wild Food Plants in the World

The use of all parts of plants (fruits, flowers, shoots, underground organs) is documented in all major climatic zones. However, the proportion of species utilized in different ecosystems may differ depending on the spectrum of life forms in a given climatic zone (e.g., more underground organs would be utilized in savannahs than in tropical rainforest ecosystems).

The kinds of edible plant organs used have changed across human history. Foragers used primarily starchy organs and fruits. They had access to large tracts of land, so could restrict themselves to using the most nutritious species. Agriculturalists have used relatively more green parts of plants as they usually have had access to smaller patches of vegetation, sometimes only their own fields. In this case, weeds growing in fields would be a primary type of wild food plants used (e.g., *quelites,* described earlier).

The pattern of the use of wild food plants is strongly affected by culture. For example, in the Amazon or in Eastern Europe wild green vegetables play a minor role, whereas in East Asia and India, they are highly prized and large numbers of species are used.

Aquatic and marsh habitats are ecosystems both particularly rich in edible plants and particularly productive; they produce a notable proportion of wild plant foods in many parts of the world.

V. WEEDS: ROLES IN CULTURES AND AGROECOSYSTEMS

Farming activity implies a simplification of the environmental structure and diversity, replacing the natural ecosystem's biodiversity with a limited number of crops and domestic animals, sometimes only single species (Altieri, 1987). Agriculture has also had a major influence on the evolution of weedy species—those particularly adapted to disturbed conditions with a high capability for colonization of newly cleared but potentially productive ground, and of high rates of reproduction and the ability to maintain their abundance under repeatedly disturbed conditions (Mohler, 2001). From an ecological point of view, weeds are the pioneers of secondary succession (Bunting, 1960). Agricultural activities have kept plant community succession in its early stages, and the environmental simplification that has characterized modern agriculture systems creates specialized habitats that favour the selection of highly competitive weeds. These species are able to adapt and survive under conditions of maximum disturbance. They often invade and colonize arable fields and can exploit ecological niches left open in croplands.

A. What Are Weeds in Conventional and Ecological Agriculture?

Commonly defined, *weeds* are plants that grow in places where they are not wanted and, because they often interfere with the growth of desired cultivated plants (as well as with some desired native plants, in the case of introduced weeds), they sometimes need to be controlled or managed. Weeds are a major source of competition with crops for light, water, air, and nutrients (Pfeiffer, 1970), and in conventional cropping systems most weeds are considered to be detrimental, because of this competition as well as sometimes hosting insect pests and plant diseases, thereby reducing yields and quality of crops. Today, about 250 plant species are universally considered weeds and the USDA Natural Resources Conservation Services counts 661 records in the "Federal and State Invasive and Noxious Weeds" database (http://plants.usda.gov/java/noxComposite). Thus, it is not surprising that in the 2004 global sales of agrochemicals amounting to US$32,6 billion (Euro 26,785), herbicides accounted for 45.4% of the total pesticide market (Agrow, 2005), and the consumption of herbicides in 2001 was 118.286 tonnes in the European Union (FAO, 2009).

However, weeds can also have a positive effect in agroecosystems. In ecological and organic agriculture, weeds are not controlled with chemical herbicides but through a "systems approach," in which weed management and agriculture are considered as part of the milieu of interactions that may be categorized as social, economic, and environmental (Swanton and Murphy, 1996). The goal of the ecological agriculture is not to eliminate weeds but to manage them. In fact, in balanced and complex ecosystems weeds do not exist as negative entities, as they are part its components. In the EU organic regulation and IFOAM norms, weed management is based on prevention methods: "The prevention of damage caused by pests, diseases and weeds shall rely primarily on the protection of natural enemies, the choice of species and varieties, crop rotation, cultivation techniques and processes heat" (from Reg CEE 834/07 art. 12 g). "Organic farming systems apply biological and cultural means to prevent unacceptable losses from pests, diseases and weeds. They use crops and varieties that are well-adapted to the environment and a balanced fertility program to maintain fertile soils with high biological activity, locally adapted rotations, companion planting, green manures, and other recognized organic practices as described in these standards" (from IFOAM Basic Standards 2005, 4.5 Pest, Disease, Weed, and Growth Management, General Principles).

Increasing crop species diversity *per se* may suppress weeds. Differences in height, canopy thickness, rooting zone and phenology are likely to influence crop and weed interactions. Concerning the weed flora in the field, a more equilibrated community tends to evolve in time under organic management. A long-term study comparing organic vs. conventional agriculture in Tuscany showed that in organically managed agroecosystems the biodiversity of weeds measured with Shannon index (Shannon and Weaver, 1963), both for weed density (number of plants m^{-2}) and biomass ($g\ m^{-2}$) of each species, increased over time since conversion from conventional methods and was higher in organic farming systems than in conventional systems treated with chemical herbicides, which resulted in a maximum discrepancy for the weeds' biodiversity (Migliorini and Vazzana, 2007).

B. The Ecological Role of Weeds

Weeds often have some negative effects on crops. Furthermore, some weeds—especially those that are introduced and invade the niches of corresponding native species—are noxious and harmful to many indigenous species and natural habitats. Much has been written about the harmful effects of weeds when introduced as invasive aliens (Crosby, 1986). Nevertheless, many weeds are important biological components of agroecosystems that may actually benefit crop plant communities. Natural habitats host wild populations of cultivated plant ancestors that often contain useful genes absent in the pool gene of their domesticated counterparts. As wild relatives of cultivated plants, many weeds can be considered important sources of biodiversity (genetic and species diversity) (Hammer *et al.*, 1997). Weeds are also key components of field margins (hedges, margin strips and semi-natural habitats associated with boundaries and ditches), the presence of which is very important ecologically. These edge habitats improve overall biodiversity and provide habitat, refuge, food and corridors for the movement of the different species of organisms in the area (Lazzerini *et al*., 2007).

Weeds can also protect against soil erosion as a natural cover crop (Gliessman *et al*., 1981). The cover of the spontaneous vegetation improves infiltration, enriches the soil water reserves, and reduces run-off of pesticides and excess nutrients (Swanton and Weise, 1991), as well as increasing soil quality through promoting microbial activity and diversity (Moreno *et al*., 2009). There may also be increased efficiency in nutrient cycling, with greater numbers and diversity of interacting organisms (Clements *et al.*, 1994). Weeds can act as "catch crops," taking up nutrients, preventing nutrient leaching and increasing overall soil quality and fertility. They are also a relatively important source of organic matter, carbon and nitrogen input in the soil when their residues and dead roots enter in the soil process of decomposition (mineralization) and building activity (humification).

Spontaneous flora is dependent on the ecological environment and is good indicator in monitoring environmental parameters like soil quality. In particular, some groups of plants are typical of acidic or sub-acidic soils (e.g., *Rumex acetosella, Anthemis arvensis, Stachys arvensis*), others of calcareous soils (e.g., *Adonis aestivialis, Nigella arvensis, Papaver rhoeas, Ranunculus arvensis, Sinapis arvensis, Veronica polita, Euphorbia cyparissias, Bromus arvensis*), others of nutrient-rich soils (e.g., *Amaranthus* spp., *Chenopodium* spp., *Euphorbia* spp., *Fumaria officinalis, Galium aparine, Mercurialis annua, Rumex obtusifolius, Sonchus* spp., *Solanum nigrum, Stellaria media, Urtica dioica*), of moist soils (e.g., *Equisetum* spp., *Mentha* spp., *Tussilago farfara, Poa trivialis*), or of salty soils (e.g., *Chenopodium* spp., *Atriplex* spp.). Other species tend to be broadly tolerant of a range of soil types (e.g,. *Cirsum arvense, Chenopodium album, Sinapis arvensis, Fallopia convolvolus*). In a biodynamic approach, weeds having specific effects on environments are called "dynamic" (Pfiffer, 1950). Stinging nettle (*Urtica dioica*) is one of these, as it enhances resistance and enriches nutrients in nearby plants, and stimulates the formation of humus in the soil. Other dynamic weeds include Scotch grass (*Cynodon dactylon),* Autumn hawkbit (*Leontodon autumnalis*) and field horsetail (*Equisetum arvensis*). Weeds can also have an allelopathic effect on the development of other more noxious weeds (Weston, 1996; Anaya, 1999; Singh *et al.*, 2003; Batish *et al.*, 2006).

As pioneer species, weeds tend to create more stable environments through helping to develop more complex communities and increasing the competition within ecosystems. Scientific evidence shows that there are significant interactions between crops, weeds and insects (Altieri and Nicholls, 2004). Cropping systems affect both weed diversity and the density of the populations of insect pests and their regulators. In particular, some weeds at their flowering stage (e.g., those of families Apiaceae, Fabaceae, Asteraceae) play an important ecological role by providing shelter and nourishment to a complex of arthropod natural regulators of pest populations (Altieri, Schoonhoven and Doll, 1977; Altieri and Whithcomb, 1979, 1980). Weeds serve as important habitat for beneficial insects, predators and parasitoides and also as alternative sources of pollen and nectar (Altieri and Whitcomb, 1979). Weeds also provide, together with crop residues, a living mulch that contributes to the detritus food web. By reducing weeds with fire or a broad spectrum herbicides it is possible to stimulate detritivores in shifting their food preference from organic dead insufficient residues to cotyledons of cereal crops (Paoletti *et al.,* 2007a). Thus, weeds can be seen from different perspectives depending on the cultural approach, environmental condition and geographical area. In the past, as well as today in some countries, many of these weedy plants are significant sources of food, fodder, fibre and medicine (Liebmann, 2001).

VI. WEEDS IN LOCAL CUISINES

In many areas in Italy and other parts of the world weeds are still gathered, especially during the spring season, mainly by the oldest female members of the communities and in rural areas (Pieroni, 1999). We will briefly illustrate in the following sections four case studies focusing on four archaic weed-based soups in Eastern Europe and Northern Italy. Weeds—and wild growing plants in general—are also sometimes used in the production of alcoholic beverages, either as flavorings, or as major ingredients, such as in dandelion wine (Szczawinski and Turner, 1978).

A. The Original Borsch

Nowadays the Russian name ***borsh*** and Polish ***barszcz*** designate a kind of vegetable soup, specifically one made with beetroots (*Beta vulgaris*). However in the past this name applied mainly to a soup made from the young shoots of hogweed, or cow-parsnip (*Heracleum sphondylium*) which in Polish bears the name ***barszcz*** and in Russian ***barshchevnikh***.

How did it happen that this shift in the meaning of the name arose? This issue fascinated professor Józef Rostafiński, a Polish botanist from Cracow, who in 1916 published a treatise on the history of the shift from eating *Heracleum* to eating beetroots. Hogweed is reported as an important food plant in Poland in the sixteenth century. In the herbal of Marcin z Urzędowa (1595) we can read: "Whoever eats hogweed, moistens his living.. . . When they make it sour in the Polish way, it is good to drink in fevers, thirst, as it alleviates thirst and cholera and it induces greed for food with its spice.. . . Garnished with egg and butter, it is good to eat on the days when they do not eat meat soup, as it works in the same way."

The use of this plant in Poland and Lithuania was also mentioned (as *Spondylium*) in John Gerarde's English herbal published in 1597. Another old account comes from Syrennius (1613): "Hogweed is familiar to everyone in our country, in Ruthenia, Lithuania and Żmudź.. . . It is useful as medicine and for food is very tasty. Both roots and leaves. However the root is more useful as medicine and leaves as food.. . . Leaves are commonly gathered in May.. . . Soup made with it, as it is made in our country, Lithuania and Ruthenia, is tasty and graceful. Either cooked on its own or with chicken or other ingredients such as eggs, cream, millet." Hogweed was the main lacto-fermented soup of Slavic nations. Hogweed's young leaves and stalks were covered with warm water and left for a few days to become sour. In favorable conditions two or three days is usually enough for the process. According to a seventeenth century archival menu, hogweed soup was served for the professors of Jagiellonian University in Cracow every Wednesday during the period of Lent and they also ate it as the main soup at Easter (Karbowiak, 1900). What is interesting is that it was called "***barszcz*** made of ***barszcz***", suggesting that another kind of ***barszcz*** soup was made with other plants, probably beetroots, which were gradually becoming popular as a vegetable (Rostafiński, 1916). Step by step, beetroots eventually completely eradicated the hogweed in this soup.

In the 18th century hogweed **barszcz** was already a rare food for poorer people only. For example Ładowski wrote that ". . . the vulgar people use hogweed to make a soup called ***Barszcz***" (Ładowski, 1783). In the same period Jundziłł (1799) gave a description of its use in Lithuania, which was probably identical to its use in Poland: "They collect young leaves, ferment them in the same fashion as other vegetables and they are frequently eaten by village people. Or, dried in the shade like celery, they are kept for further use." The sudden decline of the use of *Heracleum* in the 18th century is documented by the fact that hogweed soup is not listed in Kluk in his plant dictionary (1786). This is surprising, as Kluk was very interested in food plants and he lived in northeastern Poland, in an area adjacent to Lithuania.

According to Rostafiński hogweed soup ceased to be made in Poland in the eighteenth or nineteenth century and the last record of its use in adjacent Lithuania comes from 1845. However, Moszyński witnessed it still being made in Russia in the twentieth century, in fact is still made in some parts of the former Soviet Union nowadays, particularly in Kamtchatka. The use of hogweed was also frequently mentioned by Moszyński's informants in Belarus (Rostafiński's, query in 1883) (Łuczaj, 2008a). In fact hogweed soup was still occasionally, though rarely, made in southern Poland even up until the early twentieth century in a few villages of the Beskidy Mountains (Łuczaj and Szymański, 2007; Łuczaj, 2008b).

A plant that disappeared from the Polish menu even earlier is a relative of hogweed—ground elder, *Aegopodium podagraria.* Ground elder was sold in the market of Cracow in medieval times but later came into disuse (Maurizio, 1927). Its consumption in the past was documented in only a few villages (Łuczaj, 2008a; Pirożnikow, 2008). However its consumption in Belarus was widespread, at least until the end of the nineteenth century. The relatively small cultural importance of *Aegopodium* must be Poles' cultural choice as this wild vegetable is widespread and abundant and was commonly used in some other European countries (Hedrick, 1919).

In the Ukraine, the name "green *borsh*" designates any soup made of green vegetables, e.g., *Rumex acetosa, Chenopodium album* and *Urtica dioica,* which indicates that in the past mixed soups of many species of wild vegetables could have been more common everywhere. The above-mentioned wild plants are still occasionally sold in Ukrainian markets (information from a few Ukrainian botanists). In some parts of Ukraine (e.g., in the Uman area) the use of *Aegopodium podagraria* for green *borsh* also still occurs (Kuzemko, 2008).

In many areas in Italy and other parts of the world weeds are still gathered, especially during the spring season, mainly by the oldest female members of the communities and in rural areas (Pieroni, 1999). We will briefly illustrate in the following sections three case studies focusing on three archaic weed-based soups in Northern Italy. Weeds—and wild growing plants in general—are also sometimes used in the production of alcoholic beverages, either as flavorings, or as major ingredients, such as in dandelion wine (Szczawinski and Turner, 1978).

B. "Pistic": A Blend of Potherbs

The native populations of Friuli Venezia Giulia have always been tapping, to various degrees, the considerable local resources of vascular plants, consisting of approximately 3,380 entities (Poldini *et al.*, 2005), in order to assemble and integrate their food stock from season to season. Phytoalimurgia has had followers in Friuli Venezia Giulia as well as in other Italian regions, both in the past and in more recent years. A preliminary survey (Paoletti *et al.*, 1995) carried out in western Friuli has allowed to rediscover the custom to gather wild vernal potherbs to prepare a special dish that is known under different names depending on its area of origin: ***pistic*** (Val Colvera, in the Prealps of Friuli Venezia Giulia), ***frita*** (Carnia), ***lidùm*** (Cividale del Friuli).This preparation consists of more than 62 potherbs gathered in field margins, hay meadows, woodlands, and in the wild; these herbs occur more typically in spring. Most potherbs included in the ***pistic*** are boiled; some are also eaten raw in green salads or pan-fried with butter or lard or used in omelettes. The conclusions of this early research unveiled the pre-Roman Celtic origin of ***pistic***, which has been confirmed by etymological studies about the names of some of the potherbs blended in this dish.

However, the revived interest in wild edible vegetable species led us to undertake further research into the current knowledge about this topic in the Carnic Prealps and in the Upper Friulian Plain. This knowledge is still widespread in the area under investigation and was not reported in previous studies. From the initial interviews with informants to draft a simple list of the potherbs gathered for dietary purposes, also with the aim of preserving and safeguarding the local knowledge about edible plants, it was finally possible to make an assumption about what the possible origin of such dietary customs could be. The ecology of the adopted vegetable species and the archaeobotanical research work published for the Friulian area and the Alps in general lead investigators to assume that most of the plants that are still consumed for dietary purposes have been so since very ancient times and that new knowledge about the species used or about any different uses of them has developed over the decades. In this respect, a very special example is offered by *Crambe tataria SebeòK*, an adventitious naturalized Brassicaceous plant found in the Magredi of the western Upper Friulian Plain, the only Italian site known to host this species. Recent research (Cassola Guida, 2006) assumes that this species was already present in the Early/Middle Bronze Age (see Table 2).

C. "*Prebuggiun*": Wild Herbs Used as Food in Liguria Region, Italy

In Liguria the tradition of eating ***prebuggiun*** has very ancient origins and is widespread in the entire territory of Genoa, in particular in the eastern part of this province. It consists of a "mixture of wild or semi-domesticated potherbs collected in cultivated and abandoned fields and used, after boiling, for soups, filling for pies, omelettes and vegetable raviolis (the typical pansotti) or simply as a side-dish" (Bisio and Minuto, 1999). Actually, this tradition is popular throughout the Liguria region, though under different names. At Levanto, for example, it is simply called '***gattafin,***' whereas it is plainly referred to as '***erbette***' in the western part of the region. In their attempts to investigate this tradition, scientists have often been able to record only the vernacular names for the herbs used, which are different in the various areas of origin, and have been confronted with rather "individualized" plant collections, based on the collector's personal experience and with specific oral transmission that has allowed the handing down of this knowledge.

Nevertheless, in interviewing people who are still used to collecting wild edible plants, as well as through field surveys conducted by ethnobotanists, a fairly complete list of the species forming the ***prebuggiun*** herb collection can be compiled. It consists of a total of 38 plants, belonging to 15 families, but half of which are from Asteraceae (see Table 3). These species share similar morphological, ecological and physiological features; they are annual, biennial or rarely perennial herbaceous plants. Most are hemicryptophytes, with a basal leaf rosette, and range very widely in size, depending on their places of origin and substrate conditions (Bisio and Minuto, 1997).

Research studies have investigated the antioxidant properties of a dozen of wild herbs used to make *prebuggiun*. Among

TABLE 2
Edible plants included in the "pistic" blend.

	Edible parts	
Plant species	Boiled	Raw
Aposeris foetida (L.) Less	Lf	Bl
Aristolochia pallida Wild	Lf	
Aruncus dioicus (Walter) Fernald	Spr	
Bellis perennis L.	Lf	
Campanula trachelion L.	Lf	
Capsella bursa-pastoris (L.) Medicus L.	Lf	
Cardamine flexuosa With.	Lf	
Cardaminopsis halleri (L.)	Lf	
Carum carvi L.	Lf	Se
Centaurea nigrescens Willd	Lf	
Chenopodium album L.	Lf	
Chenopodium bonus-henricus L.	Lf	
Chenopodium polyspermum L.	Lf	
Cirsium oleraceum (L.) Scop.	Lf	
Clematis vitalba L.	Spr	
Crepis capillaris (L.) Wallr	Lf	Lf
Crepis setosa Hall.	Lf	
Erigeron annuus (L.) Pers	Lf	
Fagus sylvatica L.	Lf	
Filipendula vulgaris Moench	Lf	
Fragaria vesca L.	Lf	Fr
Galium aristatum L.	Lf	
Galium mollugo L.	Lf	
Hypochaeris maculata L.	Lf	
Hypochaeris radicata L.	Lf	Lf
Lamium purpureum L.	Lf	
Leontodon hispidus L.	Lf	
Leucanthemum vulgare Lam.	Lf	
Myosotis arvensis (L.) Hill	Lf	
Ornthogalum pyrenaicum L.	Lf, Bl	
Oxalis acetosella L.	Lf	Lf
Papaver somniferum L.	Lf	
Phyteuma spicatum L.	Lf, Bl	
Plantago lanceolata L.	Lf	
Plantago major L.	Lf	
Plantago media L.	Lf	
Polygonum persicaria L.	Lf	
Primula acaulis (L.) Hill	Lf	
Ranunculus ficaria L.	Lf	Lf
Ranunculus repens L.	Lf	
Rubus ulmifolius Schott	Spr	Fr
Rumex acetosa L.	Lf	Lf
Rumex obtusifolius L.	Lf	
Ruscus aculeatus L.	Lf	
Salvia pratensis L.	Lf	
Silene alba (Miller) Krause	Lf	
Silene dioica (L.) Clairv	Lf	
Silene vulgaris (Moench) Gorcke	Lf	

TABLE 2
Edible plants included in the "pistic" blend. *(Continued)*

	Edible parts	
Plant species	Boiled	Raw
Sonchus asper (L.) Hill	Lf	
Sonchus oleraceus L.	Lf	
Stellaria media (L.) Vill	Lf	
Tamus communis L.	Spr	
Taraxacum officinale Weber	Lf	Lf
Tragopogon pratensis L.	Lf	
Urtica dioica L.	Lf	
Veronica beccabunga L.		Lf

Note: Fl = Flowers, Lf = Leaves, Spr = Sprouts, Se = Seeds, Fr = Fruits, Bl = Blossoms.

them at least six are characterized by radical scavenging activity, similar or better than those of some foods that are well known for their antioxidant properties such as blueberry (*Vaccinium myrtillus* L.) and Verona red chicory [*Cichorium intybus* L. var. *foliosum* (Hegi) Bishoff] (Sacchetti *et al.*, 2009; Vanzani *et al.*, 2011).

TABLE 3
Edible plants included in the "prebuggiun" blend.

	Edible parts	
Plant species	Boiled	Raw
Arctium lappa L.	Lf	
Capsella bursa-pastoris (L.) Medicus	Lf	
Beta vulgaris L.	Lf	Lf
Borago officinalis L.	Lf, Fl	Lf, Fl
Brassica oleracea L. *convar. capitata*	Lf	Lf
Campanula rapunculus L.	Lf, Rt	Lf, Rt
Centranthus ruber L.	Lf	Lf
Chenopodium album L.	Lf	Lf
Cichorium indivia L.	Lf	Lf
Cichorium intybus L.	Lf	Lf
Cirsium vulgare (Savi) Ten.	Lf	
Crepis foetida L.	Lf	
Crepis vesicaria L.	Lf	
Diplotaxis muralis (L.) DC.	Lf	Lf
Foeniculum vulgare Miller	Lf	Lf
Hyoseris radiata L.	Lf	Lf
Hypochaeris radicata L.	Lf	
Inula conyza DC.	Lf	
Leontodon hispidus L.	Lf	Lf
Leontodon leysseri (Wallr)	Lf	Lf
Leontodon tuberosus L.	Lf	Lf
Papaver rhoeas L.	Lf	
Picris echioides L.	Lf	
Galium aristatum L.	Lf	
Pimpinella major L.	Lf	Lf
Plantago major L.	Lf	
Plantago lanceolata L.	Lf	
Ranunculus ficaria L.	Lf, Fl	Lf, Fl
Reichardia picroides L.	Lf	
Raphanus rhaphanistrum Strobl	Lf	
Rumex crispus L.	Lf	
Sanguisorba minor L.	Lf	Lf
Silene alba (Miller) Krause	Lf	
Silene vulgaris (Moench) Gorcke	Lf	
Sonchus oleraceus L.	Lf	
Taraxacum officinale Weber	Lf	Lf
Urospermum dalechampii L.	Lf	
Urtica dioica L.	Lf	

Note: Fl = flowers, Lf = leaves, Rt = roots

D. "Minestrella" of Gallicano

The gathering of weedy greens for the ***minestrella*** is still a ritual for many women of the village of Gallicano in the Garfagnana (upper Serchio valley) in Northwest Tuscany (Pieroni, 1999). The area of distribution of the ***minestrella*** is restricted to the territory extending from Gallicano east to the Apuan crest and the association of several boiled spontaneous vegetables is common also in the cooking traditions of other areas on the other side of the Apuan Alps (in the Versilia region) and Liguria (the northeastern region bordering Tuscany). In all these territories the domination of the Ligurian-Apuans (2nd to 3rd Centuries BC) was remarkable and we could hypothesize that the specific history of this area may have played a role in developing these culinary customs.

Weeds, whose young aerial parts are gathered during the spring in the territory of Gallicano for preparing the local vegetal soup (Minestrella) Pieroni (1999).

TABLE 4
Wild edible plants included in "Minestrella".

Allium ampeloprasum L., *A. schoenoprasum*, and *A. vineale* L.
Apium nodiflorum L.
Bellis perennis L.
Beta vulgaris L. ssp. *maritima* (L.) Thell.
Borago officinalis L.
Bunias erucago L.
Campanula rapunculus L. and *C. trachelium* L.

TABLE 4
Wild edible plants included in “Minestrella”. *(Continued)*

Cichorium intybus L.
Cirsium arvense (L.) Scop.
Crepis leontodontoides All., *C. sancta* (L.) Babcock, and *C. vesicaria* L.
Daucus carota L.
Foeniculum vulgare Miller
Geranium molle L.
Hypochaeris radicata L.
Lapsana communis L.
Leontodon hispidus L.
Lychnis flos-cuculi L.
Malva sylvestris L.
Papaver rhoeas L.
Picris echioides L. and *P. hieracioides* L.
Plantago lanceolata L. and *P. major* L.
Primula vulgaris Hudson
Raphanus raphanistrum L.
Ranunculus ficaria L.
Reichardia picroides (L.) Roth
Rumex crispus L. and *R. obtusifolium* L.
Salvia pratensis L. and *S. verbenaca* L.
Sanguisorba minor Scop.
Silene alba (Miller) Krause and *S. vulgaris* (Moench) Garcke
Sisymbrium officinale (L.) Scop.
Sonchus asper L. and *S. oleraceus* L.
Symphytum tuberosum L.
Taraxacum officinale Web.
Urtica dioica L.
Urtica urens L.
Viola odorata L.

VII. “LEAVES” IN THE MEDITERRANEAN CUISINE—A CASE STUDY IN INLAND SOUTHERN ITALY

A. Ethnotaxonomy of Food Weeds

Pieroni *et al.* (2005) studied how local women in an inland Southern Italian village, Castelmezzano, classify non-cultivated botanicals (excluding fruits). The “concept” of non-cultivated plants is not clearly expressed linguistically by local women. Most of the classification elements have the lynchpin in being or being part of the midlevel or intermediate (Berlin, 1992) category, “*fogliē*” (literally “leaves”), corresponding roughly to the concept of “edible leafy vegetables.” Moreover, even the distinction between cultivated and non-cultivated species is quite vague and fluctuant. So, for example, if the term “*fogliē*” indicates generally non-cultivated leafy vegetables, there are also a few semi-cultivated plants that would be referred to this group, as is the case with rocket (*Eruca sativa*), spinach beet (*Beta vulgaris*), and broccoli raab tops (*Brassica rapa* ssp. *rapa* Group Ruvo Baley). One of the reasons could be that cultivated species are growing in the same ecological zone, whereas *fogliē* are generally gathered, for example around home gardens in the vineyards.

On the other pole, people in the same area perceive as prototypical for non-cultivated (wild) species, mushrooms (*fungi*), and to a less extent, the young non-cultivated shoots (as like those of wild asparagus (*Asparagus acutifolius*), butcher’s broom (*Ruscus aculeatus*) and traveller’s joy [*Clematis vitalba*]), and the flower receptacles of wild artichoke (*Cynara cardunculus* ssp. *cardunculus)* and carlines (*Carlina acaulis*), which are not at all considered kind of *fogliē*.

It is interesting to underline that mushrooms and shoots are generally gathered in the secondary forests or in the hedgerows bordering the durum wheat fields, which represent the ecological zones located quite far from the village centers. *Fogliē* are instead mainly collected by women near the inhabited centre, along countryside pathways, in the vineyards or near the wheat fields. Only a few plants are gathered in the marshes. Men are the main collector of mushrooms.

Perception of “wilderness” as cultural construct seems than in the study area to be related to the distance from the inhabited village and especially to the degree of human disturbing (agricultural/pastoral) activities: what is gathered in the forest (mushrooms, wild asparagus, butcher’s brooms shoots, wild artichoke and carline) is considered “more wild” of what growing spontaneously and gathered around vineyards (*fogliē*).

These examples demonstrate how the collection of non cultivated plants is inextricably embedded with cultural concepts describing the traditional management of natural resources and the spatial organization of the natural/cultural landscape.

B. Wild Food Plants, Generational and Gender Relations, and Cultural Identity

Elderly people in Southern Italy agreed in referring us that non-cultivated vegetables are consumed nowadays to much less extent than decades ago. The reason of this shift, which has been observed in other areas in the Mediterranean as well, could be found in the changed socio-economic context: the younger generation have nearly lost the competence (Traditional Knowledge, TK) necessary to identify, gather and process in the kitchen these species, while for many informants of the middle generations consuming non cultivated vegetables is now perceived in a negative way, oft enas a symbol of a poor past.

Moreover, nowadays young women in inland Southern Italy often join the workforce through factory labor and as clericals, and rely on older women in their family (mothers, aunts, grandmothers) to care for their children while they are at work. These women have little time to carry on the traditional ways of preparing food and also to gather vegetables; they instead buy nearly all foodstuffs for the family in supermarkets and local open-air markets. For both genders of the younger and middle generation, trends towards leaving the traditional ways of living behind in the search for other living styles (reliant on pre-made meals) have played a detrimental role in the transmission and perpetuation of TK on non-cultivated vegetables and subsequently in maintaining these local products in the daily diet.

The authority of these elderly women was strong in the villages of Southern Italy while. From the authority of elderly women a long series of particular annexes are derived: managing gathering activities, organizing home gardening, and co-operating with men in the decisions concerning agriculture (which, however, was still the final prerogative of the men in the community). As the persons who had nearly total responsibility for the domestic domain, and in particular for the kitchen, elderly women were accustomed to directing everyday life in the house.

Today, of all these sources of authority, nothing remains in the hands of younger generations of women. All decisions concerning work in the fields are made by their male partners, and their role at home is weaker than before. They generally do not manage home gardens (keeping only a few flowers in the balcony); they are still the ‘queens’ of the kitchen, but the majority of have lost the knowledge associated with traditional cuisine. In some ways, they no longer have the same authority as their mothers or grandmother: this is perhaps the price that they have had to pay to become economically independent. If this new situation is partially accepted by their male partners, it is generally rejected by the oldest generations (both male and female), which at times produces deep conflicts inside families between generations (Pieroni, 2003).

On the other hand, the majority of the young women have attended school. It seems then that their mothers’ and grandmothers’ TEK has been substituted by formal education, without the latter having the same social implications as the former. At present, young women in the study area are very conscious about their muted role in the family and their broader independence (both economic and psychological) that they have finally attained. In the many open discussions that were held with young women in the Vulture area, the majority tended to automatically reject an exclusive role in domestic affairs, which was ‘functional’ in a society conjugated in the masculine form where men dominated a lot of important decision-making processes as well as all matters related to the administration of cash income.

VIII. FUTURE OF TK RELATED TO WEEDY FOOD PLANTS

Re-instilling lost TK will require time and will be heavily dependent upon the positive acceptance by the younger generations of the knowledge connected with the elderly female cosmos. Acculturation processes that take place in schools and universities could facilitate insights and ideas for the formation of new activities, which could start from the reevaluation of TK related to the world of their older relatives, which is now quickly vanishing. Revalorization of women’s domestic knowledge has to take into account the emancipatory challenges that young women have begun to pose to the community especially because of their roles in economically sustaining the family.

New visions of the relations between people and nature in the studied area will depend on whether the latter will become a significant political and cultural force. Regional agricultural and rural development policies could support the creation of innovative for-profit activities, such as the controlled gathering of weedy herbs, the re-introduction of old and archaic crops and handicrafts, the development of agro- and eco-tourism, farmers’ markets, the management of natural and cultural pathways, and ethno-culinary events promoting regional and specialty food niches (e.g., Slow Food circuits).

Local women’s co-peratives or enterprises comprised of women belonging to different generations could become the protagonist of the implementation of the heritage related to wild food plants in eco-sustainable interdisciplinary projects, as a few examples of small female-run enterprises in other regions in the Mediterranean show.

They could develop strategies to enhance TEK transmission between elderly women and the new generations within local schools, sustaining the gathering of wild plants and maybe decreasing the gap between generations. Moreover, they could incorporate conservation of both natural and cultural/linguistic resources with economically profitable small-scale production of food plant derivatives and local typical food products, managed by women.

Traditional consumption of food weeds is than strongly embedded with unique cultural aspects relating local people and their management of the natural environment. Revalorization of this TK will have necessarily to pass also through its sustain via a more acute education frameworks in the schools/universities, but also maybe through substantial changes in the agenda of many national food and local policy-makers and cultural stakeholders in the Mediterranean: sustaining food agro-biodiversity could only have a sense if the efforts will take in account the inextricably connected cultural heritage, what we nowadays call “bio-cultural diversity.”

ACKNOWLEDGMENTS

We are indebted to Sally L. Benjamin for her careful and helpful review of this manuscript.

REFERENCES

Agrow. 2005. ‘First growth in global agrochemical market for a decade’, Report no. 466, 18 February 2005. published by INFORMA UK SN 0268 313X www.agrow.com

Altieri, M. A. 1987. *Agroecology: The Scientific Basis of Alternative Agriculture*. Westview Press, Boulder, CO.

Altieri, M. A., and Nicholls, C. I. 2004. *Biodiversity and Pest Management in Agroecosystems*. Haworth Press, NY.

Altieri, M. A., Schoonhoven, A.V., and Doll, J. D. 1977. The ecological role of weeds in insect pest management systems: A review illustrated with bean (*Phasoleus vulgaris* L.) cropping systems. *The Int. J. of Pest Manag.* **23**: 195–205.

Altieri, M. A., and Whithcomb, W. H. 1979. The potential use of weeds in the manipulation of beneficial insects. *Hort. Sci.* **14:** 12–18.

Altieri, M. A., and Whithcomb,W. H. 1980. Weed manipulation for insect management in corn. *Environ. Manage.* **4:** 483–489.

Anaya, A. L. 1999. Allelopathy as a tool in the management of biotic resources in the agroecosystems. *Crit. Rev. Plant Sci.* **18:** 697–739.

Anderson, M. K. 2005. *Tending the Wild: Native American Knowledge and the Management of California's Natural Resources.* University of California Press, Berkeley.

Arnason, T. J., Hebda, R. J., and Johns, T. 1981. Use of plants for food and medicine by native peoples of eastern Canada. *Can. J. Bot.* **59:** 2189–2325.

Batish, D. R., Singh, H. P., Kohli, R. K., and Dawra, G. P. 2006. Potential of allelopathy and allelochemicals for weed management. **In**: *Handbook of Sustainable Weed Management*. pp. 220–267. Singh, H. P., Batish, D. R., and Kohli, R. H., Eds., Haworth Press, New York.

Balée, W. 1994. *Footprints of the Forest: Ka'apor Ethnobotany – The Historical Ecology of Plant Utilization by an Amazonian People*. Columbia University Press, NY.

Berkes, F. 2008. Traditional ecological knowledge and resource management. **In**: *Sacred Ecology.* Second Edition, Taylor & Francis, Philadelphia, PA.

Bisio A., and Minuto, L., 1997. Il preboggiun: leggenda e tradizione di una miscela di erbe selvatiche. **In**: *Il Cibo e il Corpo/Food and Body. Dal Cibo alla Cultura, dalla Cultura al Cibo/From Food to Culture, from Culture to Food.* pp. 197–229. Guerci, A. Ed., Erga Edizioni.

Bisio, A., and Minuto, L. 1999. The prebuggiun. **In**: *Erbi Boni, Erbi degli Streghi. Good Weeds, Witches' Weeds*. pp. 34–36. Pieroni, A., Ed., Cologne, Koln.

Blurton Jones, N. G., Hawkes, K., and Draper, P. 1994a. Foraging returns of Kung adults and children: Why didn't Kung children forage? *Journal of Anthropological Research* **50:** 217–248.

Blurton Jones, N. G., Hawkes, K., and Draper, P. 1994b. Differences between Hadza and Kung children's work: original affluence or practical reason? **In:** *Key Issues in Hunter-Gatherer Research.* pp. 189–215. Burch, E. S, Ellana L. J., Eds., Oxford, Berg.

Boyd, R. 1999. *Indians, Fire and the Land in the Pacific Northwest*. Oregon State University Press, Corvallis.

Bunting, A. H. 1960. Some reflections on the ecology of weeds. **In**: *The Biology of Weeds*. pp. 11–26. Harper, J. L. Ed., Blackwell Scientific Publishers, Oxford, UK.

Butură, V. 1979. *Enciclopedie de Etnobotanică Românescă.* Editura Ştiinţifică şi Enciclopedică, Bukareszt.

Bye, Jr., R. A. 1981. Quelites—ethnoecology of edible greens-past, present, and future. *Journal of Ethnobiology*, **1:** 109–125.

Cappelletti, E.M., Sacchetti, L. E., Rascio, N., Camani A., Cassina, G., Salmaso, O., Torres, F., Lopez Hernandez, D., and Paoletti, M.G. 2002. Preliminary data on the acclimatization of Amazonian Solanum (sect. Lasiocarpa) species at the Botanic Garden of Padua. *Proceedings Eurogarden* 2000.

Cassola Guida, P. 2006. Nuove note di Protostoria friulana. **In**: *Tracce Archeologiche di Antiche Genti, la Protostoria in Friuli.* pp. 17–50. Corazza, S., Simeoni, G., Zendron, F. Circolo culturale Menocchio, Montereale Valcellina.

Clements, D. R., Weise S. F., and Swanton, C. J. 1994. Integrated weed management and weed species diversity. *Phytoprot*. **75:** 1–18.

Crosby, A. 1986. *Ecological Iimperialism: The Biological Expansion of Europe, 900-1900*. Cambridge University Press, Cambridge, UK.

Crowe, A. 1981. *A Field Guide to the Native Edible Plants of New Zealand*. Penguin Books, London, UK.

Darby, M. C. 1996. *Wapato for the People: An Ecological Approach to Understanding the Native American Use of* Sagittaria latifolia *on the Lower Columbia River*. M.A. Thesis, Department of Anthropology, Portland State University, Portland, OR.

Deur, D., and Turner, N. J. 2005. "Keeping it Living" *Traditions of Plant Use and Cultivation on the Northwest Coast of North America*. University of Washington Press, Seattle and UBC Press, Vancouver.

Dickson, J. H., Oeggl, K. and Handley, L. 2003. The Iceman reconsidered. *Sci. Amer.* **288:** 70–79.

Dreon A. L., and Paoletti, M. G. 2009. The wild food (plants and insects) in western Friuli local knowledge (Friuli-Venezia Giulia, North Eastern Italy). Konrad Thaler Memorial book, Contrib. *Nat. Hist.* **12**(1): 461–488.

Eidlitz, K. 1969. *Food and Emergency Food in the Circumpolar Area.* Studia Ethnographica Upsaliensia, Vol. 32.

Eljasz-Radzikowski, S. 1897. Polish Tatra Highlanders [in Polish]. *Lud* **3:** 225–272.

FAO (Food and Agricultural Organization). 1988. *Traditional Food Plants.* FAO Food and Nutrition Paper 42, Rome, Italy.

FAO. 2009. FAOSTAT database available at http://faostat.fao.org

Gerarde, J. 1597. *The Herball or Generall Historie of Plantes.* John Norton, London.

Gliessman S. R., Garcia, E. R., and Amador, A. M. 1981. The ecological basis for the application of traditional agriculture technology in the management of tropical agro-ecosystems. *Agro-ecosystems* **7:** 173–185.

Hammer, K., Gladis, T., and Diederichsen, A..1997. Weeds as genetic rresources. *Plant Genetic Resource Newsletter* **111:** 33–39.

Hedrick, U. P. 1972. *Sturtevant's Edible Plants of the World.* (originally published 1919) Dover Publications, New York.

Hu, S.Y. 2005. *Food Plants of China.* The Chinese University Press, Hong Kong.

Hunn, E. S. 2002. Evidence for the precocious acquisition of plant knowledge by Zapotec children. **In**: *Ethnobiology and Biocultural Diversity.* pp. 604–613. Stepp, J.R., Wyndham, F.S., and Zarger, R.K. Eds., International Society of Ethnobiology, Athens, GA.

Hussain, M. A. 1987. *Promoting Under-exploited Food Plants in Africa.* A brief for policy makers. Food Policy and Nutrition Division, FAO, Rome.

Janicka-Krzywda, U. 2008. Wild food plants in the Mount Babia Góra (West Carpathians) area [in Polish]. **In:** *Proceedings of the conference "Wild edible plants - a forgotten natural resource.*" pp. 151–159. Łuczaj, Ł., Ed., Arboretum i Zakład Fizjografi i w Bolestraszycach, Bolestraszyce.

Jędrusik, M. 2004. *Fungi and wild plants in the food of the Polish countryside (using data from 82 villages throughout Poland)* [in Polish]. Master's thesis, Silesian University, Ethnology, Cieszyn.

Johns, T., and Kubo, I. 1988. A survey of traditional methods employed for the detoxification of plant foods. *J. Ethnobiol.* **8:** 81–129.

Jundziłł, J. 1799. *Applied Botany* [in Polish]. Vilnius.

Karbowiak, A. 1900. *Dinners of Jagiellonian University professors in the 16*th *and 17*th *century* [in Polish]. Towarzystwo Miłoników Historyi i Zabytków Krakowa, Kraków.

Kennedy, J. 2009. Bananas and People in the Homeland of Genus Musa: Not just pretty fruit *Ethnbotany Research and Applications* **7:** 179–197.

Kluk, K. 1805-1811 (reprint of 1786) *Plant Dictionary* [in Polish]. Drukarnia Xięży Piarów, Warszawa.

Kołodziejska-Degórska I. 2008. What to use for tea: wild food plants in Polish villages of southern Bukovina (Romania) [in Polish]. **In:** *Proceedings of the Conference "Wild Edible Plants - A Forgotten Natural Resource.*" pp. 219–226. Łuczaj, Ł., Ed., Arboretum i Zakład Fizjografii w Bolestraszycach, Bolestraszyce.

Konlande, J. E., and Robson, J. R. K. 1972. The nutritive value of cooked camas as consumed by Flathead Indians. *Ecol. Food and Nutrition* **2:** 193–195.

Kubiak-Martens, L. 1996. Evidence for possible use of plant foods in Palaeolithic and Mesolithic diet from the site of Calowanie in the central part of the Polish Plain. *Vegetation History and Archaeobotany* **5:** 33–38.

Kuhnlein, H., Erasmus, B., Creed-Kanashiro, H., Englberger, L., Okeke, C., and Turner, N. Allen, L., and Bhattacharjee, L. 2006. Indigenous Peoples' Food Systems for Health: Finding Interventions that Work. *Public Health and Nutrition* **9**(8): 1013–1019.

Kuhnlein, H. V., Erasmus, B. and Spigelski, D. (Eds.). 2009. *Indigenous Peoples' Food Systems. The many dimensions of culture, diversity and environment for nutrition and health*. FAO. Food and Agriculture Organization of the United Nations. Centre for Indigenous Peoples' Nutrition and Environment, Rome, Italy.

Kuhnlein, H. V., and Turner, N. J. (URL version Published online 2009; originally published 1991). *Traditional Plant Foods of Canadian Indigenous Peoples. Nutrition, Botany and Use*. Volume 8. In: Food and Nutrition in History and Anthropology, edited by S. Katz. Gordon and Breach Science Publishers, Philadelphia, PA; URL: http://www.fao.org/wairdocs/other/ai215e/ai215e00.HTM (UN Food and Agriculture Organization, FAO, Rome).

Kuzemko, A. 2008. Wild food plants in the meadow communities of Ukraine. **In:** *Proceedings of the Conference "Wild Edible Plants – a Forgotten Natural Resource."* pp. 243–251. Łuczaj, Ł., Ed., Arboretum i Zakład Fizjografii w Bolestraszycach, Bolestraszyce.

Ładowski, R. 1783. *Natural History of the Kingdom of Poland* [in Polish]. Drukarnia Ignacego Gröbla, Kraków.

Lazzerini, G., Camera, A. Benedettelli, S., and Vazzana, C. 2006. The role of field margins**.** *Ital. J. Agronomy/Riv. Agron*. 2007, **2:** 115–122.

Lehr, U. 2000. Gift of nature - mushrooms. **In**: *Food from Nature. Attitudes, Strategies and Culinary Practices*. pp. 155–169, Lysaght, P., Ed., *Acta Academiae Regiae Gustavi Adolphi* 71.

Liebman, M., and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. *Ecol. Applic.* **3:** 92–122.

Łuczaj, Ł. 2008a. Wild food plants in Józef Rostafiński's questionnaire of 1883 [in Polish]. *Wiadomości Botaniczne* **52:** 39–50.

Łuczaj, Ł. 2008b. Archival data on wild food plants eaten in Poland in 1948. *J. Ethnobiology and Ethnomedicine* **4:** 4.

Łuczaj, Ł., and W. Szymański. 2007. Wild vascular plants gathered for consumption in the Polish countryside: a review. *J. Ethnobiology and Ethnomedicine* **3:** 17.

Malaisse, F. 1997. *Se Nourrir en Forêt Claire Africane. Approche Ecologique et Nutritionelle*. Les Presses Agronomiques de Gembloux, pp. 384

Marcin z Urzędowa. 1595. *Zielnik.* Kraków.

Marciniak M. 2008 Wild food plants in the rural culture of the eastern part of the Polish Carpathians [in Polish]. **In:** *Proceedings of the Conference "Wild edible plants - a Forgotten Natural Resource"*. pp. 125–132. Łuczaj, Ł., Ed., Arboretum i Zakład Fizjografi i w Bolestraszycach, Bolestraszyce.

Maurizio, A. 1926. *Plant Food in the History* [in Polish]. Kasa Mianowskiego, Lwów.

Maurizio, A. 1927. *Geschichte unserer Pflanzennahrung, von den Urzeiten bis zur Gegenwart.* Paul Parey, Berlin.

McCune, L. M. 1999. Canadian boreal forest indigenous medicinal plant treatments in relation to non-insulin dependent diabetes mellitus. PhD dissertation, McGill University, Montreal, Quebec.

Migliorini, P., and Vazzana, C. 2007. Biodiversity Indicators for sustainability evaluation of conventional and organic agro-ecosystems. *Ital. J. Agron. / Riv. Agron*. **2:** 101–106.

Minnis, P., and Elisens, W. (Eds). 1999. *Biodiversity and Native North America*. University of Oklahoma Press, Norman, OK.

Mohler, C. L. 2001. Weed life history: identifying vulnerabilities. **In:** *Ecological Management of Agricultural Wee*ds. pp. 40–98. Liebman, M., Mohler, C. L., and Staver, C. P. Eds., Cambridge University Press, UK.

Moreno, B., Garcia-Rodriguez, S., Cañizares, R., Castro, J. and Benítez, E. 2009. Rainfed olive farming in south-eastern Spain: Long-term effect of soil management on biological indicators of soil quality. *Agric. Ecosystems & Environment* **131:** 333–339.

NAC (National Academic Council). 1989. *The Lost Crops of the Incas*. National Academy Press, Washington DC.

Paoletti, M. G. 2004. Biodiversity Management and Loss of Traditional Knowledge in the Largest Forest of the Amazon. Examples from Amazonas, Venezuela and Ecuador. *International Symposium. Tropical Forests in a Changing Global Context*. Royal Academy of Overseas Sciences, United Nations Educational, Scientific and Cultural Organization, Brussels, 8-9 November, 2004: 93–111.

Paoletti, M. G. (Ed.) 2005. *Ecological Implications of the Use of Minilivestock. Insects, Rodents, Frogs and Snails*. Science Publishers, Enfield, NH.

Paoletti M. G., Dreon A. L., and Lorenzoni, G. G. 1995. Edible weeds "Pistic" found in W. Friuli (N.E. Italy). *Econ. Bot.* **49**(1): 26–30.

Paoletti, M. G., and Dufour, D. L. 2005. Edible invertebrates among Amazonian Indians: a critical review of disappearing knowledge. **In**: *Minelivestock. Enfiels*. pp. 293–342. Paoletti, M. G. Ed., Science Publishers, Enfield, NH.

Paoletti M. G., Thomson L. J., and Hoffmann, A. A. 2007. Introduction. invertebrate bioindicators in Australia. S.I. *Exper. J. Australian Agric.* **47**(4): 379–383.

Paoletti M. G., Tsitsilas A., Thomson L. J., Taiti S., and Umina, P. A. 2007a. The flood bug, *Australiodillo bifrons* (Isopoda: Armadillidae): a potential pest of cereals in Australia? *Appl. Soil Ecol.* **39:** 76–83. I.F. 1.92.

Peacock, S. L. 1998. *Putting Down Roots: The Emergence of Wild Plant Food Production on the Canadian Plateau*. PhD dissertation, University of Victoria, Victoria, BC.

Pfeiffer, E.E. 1970. *Weeds and What They Tell*. Bio-Dynamic, Wyoming. Rhode Island.

Phillips, R. 1983. *Wild Food: A Unique Photographic Guide to Finding, Cooking and Eating Wild Plants, Mushrooms and Seaweeds*. Pan Books, London.

Pieroni A. 1999. Gathered wild food plants in the upper valley of the Serchio River (Garfagnana), central Italy. *Economic Botany* **53:** 327–341.

Pieroni, A. 2003. Wild food plants and Arbëresh women in Lucania, Southern Italy. **In**: *Women & Plants*, pp. 66–82, Howard, P.L. (Ed.), *Case Studies on Gender Relations in Biodiversity Management & Conservation*. Zed Press, London, UK.

Pieroni, A. 2005. Gathering food from the wild. **In**: *The Cultural History of Plants*. pp. 29–43. G. Prance and Nesbitt, M., Eds., Taylor & Francis, New York.

Pieroni, A., Nebel, S., Santoro, R. F., and Heinrich, M. 2005. Food for two seasons: culinary uses of non-cultivated local vegetables and mushrooms in a south Italian village, *Int. J. Food Sci. and Nutr.* **56:** 245–272.

Piórecki, J. 2008. *Water caltrop Trapa natans – a forgotten edible plant* [in Polish]. **In**: *Proceedings of the conference "Wild edible plants - a forgotten natural resource".* pp. 13–17. Łuczaj, Ł., Ed., Arboretum i Zakład Fizjografii w Bolestraszycach, Bolestraszyce.

Piperno, D. R., and Pearsall, D. M. 1998. *The Origins of Agriculture in the Lowland Neotropics*. Academic Press, New York.

Pirożnikow, E. 2008. Traditional use of wild medicinal and food plants in the eastern Podlesie region [in Polish]. **In:** *The Knyszyn Forest Landscape Park in the System of Nature Protection and Environmental Education.* pp. 64–79. Gorniak, A., Poskrobko, B., Eds., Park Krajobrazowy Puszczy Knyszyńskiej, Supraś. Proceedings of the conference "Landscape parks in the beginning of the 21st century - ecological education yesterday and today: a case study of the Knyszyn Forest Landscape Park", 27-28.05.2008.

Poldini, L., Vidali, M., and Comin, S. 2005. Stato delle conoscenze floristiche in Friuli Venezia Giulia. **In:** *Stato delle Conoscenze sulla Flora Vascolare d'Italia.* pp. 123–126. Scoppola, A., Blasi, C. Palombi Editore, Roma.

Posey, D. A., and Plenderleith, K. 2004. *Indigenous. Knowledge and Ethics*. Routledge, New York.

Rascio N., Camani A., Sacchetti L., Cassina G., Torres F., Cappelletti E. M., Moro, I., and Paoletti, M. G. 2002. Acclimatization trials of some Solanum species from Amazonas Venezuela at the Botanic Garden of Padova. *Econ. Bot.* **56**(4): 306–314.

Rilievo, I. 2008. Il progetto dell'orto.**In**: *La Storia, l'Ambiente, il Progetto di un Orto Officinale a San Fruttuoso di Capodimonte (GE)*. pp. 22–23. Elaborato di Laurea - Facoltà di Scienze MM. FF. NN. - Università degli Studi di Padova.

Rostafiński, J. 1916. *About the Names of Borsch, Beet and Hogweed* [in Polish]. Akademia Umiejętności, Kraków.

Sacchetti, L. E., Vanzani, P., Rossetto, M., De Marco, V., Gomiero, T., Rigo, A., and Paoletti, M. G. 2009. *Antioxidant Properties of Wild Plants Used as food in the Mediterranean Basin.* The 3rd Congress of the International Society of Nutrigenetics/Nutrigenomics—Program Book—Poster Abstracts Addendum—October 21–23, 2009–Natcher Conference Center National Institutes of Health, Bethesda, Maryland.

Senos, R., Lake, F., Turner, N., and Martinez, D. 2006. Traditional ecological knowledge and restoration practice in the Pacific Northwest. **In**: *Encyclopedia for Restoration of Pacific Northwest Ecosystems*. pp. 393–426. Apostol, D. Ed., Island Press, Washington, DC.

Shannon, C. E., and Weaver, W. 1963. *The Mathematical Theory of Communication.* University of Illinois Press, Urbana.

Singh H.P ., Batish D. R., Kohli R. K. 2003. Allelopathic interactions and allelochemicals: New possibility for sustainable weed management. *Crit. Rev. in Plant Sci.* **22:** 239–311.

Stepp, J. R., and Moerman, D. E. 2004. The importance of weeds in ethnopharmacology. *Journal of Ethnopharmacology*, **75:** 19–23.

Strecker, L. 2007. *Die Ethnobotanik der Kamtschatka-Halbinsel. Erfassung und Beschreibung des Datenmaterials in Präsowjetischen, Nicht-Russischen und Einigen Rezenten Quellen.* Wissenschaftliche Hausarbeit zur Erlangung des akademischen Grades einer Magistra Artium der Universität Hamburg (MA Thesis, University of Hamburg, Germany).

Stross, B. 1973. Acquisition of botanical terminology by Tzeltal children. **In:** *Meaning in Mayan Languages*. pp. 107–141. Edmonson, M. S., Ed., Mouton, The Hague.

Swanton, C. J., and Murphy, S. D. 1996. Weed science beyond the weeds: The role of Integrated Weed Management (IWM). *Weed Sci.* **44:**437–445.

Swanton, C. J., and Weise, S. F. 1991. Integrated weed management: the rationale and approach. *Weed Technol.* **5:** 657–663.

Syrennius, S. 1613. *Herbal*. Kraków.

Szczawinski, A. F., and Turner, N. J. 1978. *Edible Garden Weeds of Canada. Edible Wild Plants of Canada No. 1.* National Museum of Natural Sciences, National Museums of Canada, Ottawa.

Szczawinski, A. F., and Turner, N. J. 1980. *Wild Green Vegetables of Canada. Edible Wild Plants of Canada No. 4.* National Museum of Natural Sciences, National Museums of Canada, Ottawa.

Szulczewski, J. W. 1996. *A Song Without the End. Selected Works.* Łysiak, W., Ed. [in Polish]. PSO, Poznań.

Szymański, W. M. 2007. *Efficiency of Gathering Wild Food Plants of Poland* [in Polish]. Master's Thesis, Białystok University, Biology and Chemistry Department, Białystok.

Tanaka, T. 1976. *Encyclopaedia of Edible Plants of the World.* Keigaku Publishing, Tokyo.

Turner, N. J. 1995. *Food Plants of Coastal First Peoples.* University of British Columbia Press, Vancouver and Royal British Columbia Museum, Victoria.

Turner, N. J. 1997. *Food Plants of Interior First Peoples.* University of British Columbia Press, Vancouver and Royal British Columbia Museum, Victoria.

Turner, N. J. 2003. The ethnobotany of "edible seaweed" (Porphyra abbottiae Krishnamurthy and related species; Rhodophyta: Bangiales) and its use by First Nations on the Pacific Coast of Canada. *Can. J. Bot.* **81**(2): 283–293.

Turner, N. J., Ari, Y., Berkes, F., Davidson-Hunt, I., Fusun Ertug, Z., and Miller, A. M. 2009. Cultural management of living trees: An international perspective. **In**: *Indigenous Resource Management: Past, Present and Future*. Lepofsky, D. Ed., Special Issue. *J. Ethnobiol.* **29**(2): 237–270.

Turner, N. J., and Burton, C. M. 2010. Soapberry: unique northwestern foaming fruit. **In:** *Festscrift for Thomas M. Hess*. Beck, D., and Rowicka, G. L. Eds., SURFgroepen, Netherlands. pp 278–305.

Turner, N. J., and Davis, A. 1993. "When everything was scarce": The role of plants as famine foods in northwestern North America. *J. Ethnobiol.* **13**(2): 1–28.

Turner, N. J., and Peacock, S. 2005. Solving the perennial paradox: Ethnobotanical evidence for plant resource management on the Northwest Coast. **In**: *"Keeping it Living": Traditions of Plant Use and Cultivation on the Northwest Coast of North America*. pp. 101–150. Deur, D., and Turner, N. J., Eds., University of Washington Press, Seattle and UBC Press, Vancouver.

Turner, N. J., Smith, R. Y., and Jones, J. T. 2005. "A fine line between two nations": Ownership patterns for plant resources among Northwest Coast Indigenous Peoples – implications for plant conservation and management. **In**: *"Keeping It Living": Traditions of Plant Use and Cultivation on the Northwest Coast of North America*. pp. 151–180. Deur, D., and Turner, N. J., Eds., University of Washington Press, Seattle and UBC Press, Vancouver.

Turner, N. J., and Szczawinski, A. F. 1978. *Wild Coffee and Tea Substitutes of Canada. Edible Wild Plants of Canada* No. 2. Ottawa: National Museum of Natural Sciences, National Museums of Canada.

Turner, N. J., and Szczawinski, A. F. 1979. *Edible Wild Fruits and Nuts of Canada. Edible Wild Plants of Canada* No. 3. Ottawa: National Museum of Natural Sciences, National Museums of Canada.

Turner, N. J., and von Aderkas, P. 2009. *The North American Guide to Common Poisonous Plants and Mushrooms. How to Identify More Than 300 Toxic Plants Found in Homes, Gardens, and Open Spaces*. Timber Press, Portland, OR.

Vanzani, P., Rossetto, M., De Marco, V., Sacchetti, L. E., Paoletti, M. G., and Rigo, A. 2011. Wild Mediterranean plants as traditional food: A valuable source of antioxidants. *J. Food Sci.* **76**(1): 46–51.

Walsh, F. 2009. *To Hunt and to Hold: Marty Aboriginal people's uses and knowledge of their country, with implications for co-management in Karlamilyi (Rudall River) National Park and the Great Sandy Desert, Western Australia*. The University of Western Australia, Crawley, Western Australia.

Weston, L. A. 1996. Utilization of allelopathy for weed management in agroecosystems. *Agron. J.* **88:** 860–86.

Zarger, R. K., and Stepp, J. R. 2004. Persistence of botanical knowledge among Tzeltal Maya children. *Curr. Anthrop.* **45**(3): 413–418.

Zohary, D. 2004. Unconscious selection and the evolution of domesticated plants. *Econ. Bot.* **58**(1): 5–10.

Critical Reviews in Plant Sciences, 30:226–237, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 0735-2689 print / 1549-7836 online
DOI: 10.1080/07352689.2011.554497

Innovative Education in Agroecology: Experiential Learning for a Sustainable Agriculture

**C. A. Francis,[1] N. Jordan,[2] P. Porter,[2] T. A. Breland,[3] G. Lieblein,[3]
L. Salomonsson,[4] N. Sriskandarajah,[4] M. Wiedenhoeft,[5] R. DeHaan,[6]
I. Braden,[7] V. Langer[8]**
[1]*Department of Agronomy & Horticulture, University of Nebraska, Lincoln, Nebraska, USA*
[2]*Department of Agronomy & Plant Genetics, University of Minnesota, St. Paul, Minnesota, USA*
[3]*Institute of Plant and Environmental Sciences, Norwegian University of Life Science, Ås, Norway*
[4]*Swedish University of Agricultural Sciences, Uppsala, Sweden*
[5]*Iowa State University, Ames, Iowa, USA*
[6]*Dordt College, Sioux Center, Iowa, USA*
[7]*Southeast Missouri State Univ., Cape Girardeau, Missouri, USA*
[8]*University of Copenhagen, Denmark*

Table of Contents

The transdisciplinary field of agroecology provides a platform for experiential learning based on an expanded vision of research on sustainable farming and food systems and the application of results in creating effective learning landscapes for students. With increased recognition of limitations of fossil fuels, fresh water, and available farmland, educators are changing focus from strategies to reach maximum yields to those that feature resource use efficiency

---

Address correspondence to C. A. Francis, Department of Agronomy & Horticulture, University of Nebraska, Lincoln, Nebraska, USA. E-mail: cfrancis2@unl.edu

Referee: Prof. Richard Bawden, Michigan State University, Fellow and Director of the Systemic Development Institute (SDI), and a Professor Emeritus at the University of Western Sydney.

and resilience of production systems in a less benign climate. To help students deal with complexity and uncertainty and a wide range of biological and social dimensions of the food challenge, a whole-systems approach that involves life-cycle analysis and consideration of long-term impacts of systems is essential. Seven educational case studies in the Nordic Region and the U.S. Midwest demonstrate how educators can incorporate theory of the ecology of food systems with the action learning component needed to develop student potentials to create responsible change in society. New roles of agroecology instructors and students are described as they pursue a co-learning strategy to develop and apply technology to assure the productivity and security of future food systems.

Keywords action education, service learning, transdisciplinary education, systems education, holistic learning, integrated systems

I. INTRODUCTION TO SYSTEMS AND EXPERIENTIAL LEARNING

As global competition for land, water, and fossil fuels intensifies due to growing human population, we are facing unprecedented challenges in designing both research strategies and educational programs to help future professionals prepare to serve society. We applaud the impacts of the Green Revolution on yields of predominant cereal crops, and the effects of that research on alleviating hunger in many countries. Yet it is becoming increasingly apparent that other socio-economic and environmental factors must also be considered if we are to chart an effective course for the future. Based on over a decade of farming systems research and teaching practical field courses at universities in the United States and the Nordic Region, we are convinced that the transdisciplinary field of agroecology offers great promise to: 1) expand the vision in research on sustainable agricultural systems, and through this research, 2) inform the design of effective learning landscapes for students who want to make an impact on future food and farming systems. The central goal is to develop competencies of students in agroecology.

Agroecology research and teaching emerges from a focus on sustainable agriculture, gathering increased momentum as more people recognize the limits of fossil fuels, fresh water, and available farmland. Most scientists agree that global climate change will impact production, and that much of our current productivity and the resulting growth in human numbers have been due to development of a technology appropriate to cheap fossil fuels, available water, and relatively benign climates that have characterized the past two centuries (Kirschenmann, 2009). With looming constraints to productivity due to limited resources and an imperative to feed a growing human population, agricultural and food systems scientists are looking at larger systems issues as well as alternative research methods and strategies that will contribute to solutions in the context of resource scarcity. Likewise, students will be faced with challenges full of uncertainty and increased complexity, needing a multi-perspective approach to seek solutions.

Sustainable agriculture provided an umbrella for valuable research and education for the past two decades. Although the term is ambiguous—no one would claim to be designing a *non-sustainable* system—it is a useful concept and statement of purpose, if not a precise goal nor menu for specific farming systems or practices. The term has been overused and adopted by groups across the spectrum of political persuasion and environmental perspective, from Greenpeace to Monsanto. This has added to confusion and caused loss of credibility. Some universities have chosen to focus on the study of *agroecology*, a term broadly defined as *the ecology of food systems* (Francis *et al.*, 2003), and a rigorous academic area closely linked to practice and meaningful action. We adopt this definition for education in agroecology, while recognizing that the term has been used more narrowly to explain agriculture in ecological terms (Altieri, 1983; Gliessman, 1984).

Richard Bawden's article on systems thinking and research is frequently cited by agricultural educators as a key reference point for application of systems principles in the educational arena (Bawden, 1991). His pioneering experiential learning program at University of Western Sidney in Hawkesbury, with students working with farmers and ranchers near the university, provided incentive to implement on-farm education components in programs in other countries. The concept of double loop learning and building on experience was summarized by Sriskandarajah *et al*. (1990) in the context of farming systems research and extension. Wilson and Morren (1990) provided synthesis of methods around systems research, in a text frequently used in teaching integrated systems theory and practice. These resources bring a logical combination of theory and application to put the principles of systems analysis to practical use. We build on the strategy for competence development (Bawden, 2007a).

The systems approach in agriculture is a multi-perspective way of seeing the world, distinct from that employed by single disciplines. Holistic thinking requires a systemic approach to observing and analyzing complex situations in agriculture and food systems. While research on individual components of the system is often essential, this work is most valuable when conducted with an appreciation of the whole system in mind. When looking at the likely impacts of a new high-yielding wheat variety, for example, it is important to consider the prices and long-term availability of needed inputs, the impacts on the local and regional environment, and the social consequences of introducing this variety, such as farm size, concentration of markets, and distribution of benefits. These are factors not often considered by the plant breeder who is closely focused on the goal of increasing genetic production potential. Agroecology provides a framework within which to study the multiple consequences of new technology introduction.

Another unique characteristic of agroecology as applied in research programs in the United States and Norway is the blending of biophysical and social science methods, the latter sometimes called *soft systems methods* (Checkland, 1981; Checkland and Scholes, 2001). Employing such methods as surveys, interviews, focus groups, and personal observations of people and groups, these research and learning strategies are appropriate to evaluate many aspects of human activity systems, including those that involve farming and food. This window on the human component of systems complements the observations and measurements of crop and animal enterprises, analysis of short-term economics, and evaluation of environmental impacts on farm and in the landscape. When combined with biological methods, this strategy provides multiple windows on the systems of interest, and allows us to approach situations that are filled with multiple interacting dimensions and uncertainty with some confidence of understanding complexity. This wide range of methods has been employed in a diverse array of MSc thesis projects: waste water for vegetable production in Havana, composting organic waste in Yaounde, food policy councils in Canada, and growth of organic farming in Colombia. In Norway, the thesis projects have included meat goat production in the mountains, agrotourism in the north, farmers markets across the country, and farmers as teachers on the west coast. This combined strategy to research can open vistas to innovative perspectives on food and farming systems challenges that would not be possible with single discipline research and education methods.

An important academic foundation for experiential learning was provided by the legendary John Dewey (1916), who maintained that all learning must be put into context of prior knowledge and experience, and that the key was "learning by doing." His theories were employed widely in agriculture for half a century, as colleges featured farm practice experiences that were tied closely to academic topics in the classroom. Field experience requirements were abandoned along with two-year practical degrees in most U.S. landgrant universities. Study of agriculture evolved into genetics, entomology, engineering, pathology, and economics as individual disciplines, organized into departments and majors. Breadth requirements assured that students were exposed to other disciplines, but most topics were taught as stand-alone courses rather than as components of complex systems. Many of the practical advantages of general agriculture education and appreciation of systems complexity eroded in favor of biotechnology, macroeconomics, and environmental science, each studied as independent and self-contained disciplines with their own language and culture.

Courses in sustainable agriculture, organic farming, and integrated agricultural development gained a dedicated following in some universities in the 1990s. These were organized and driven by a few faculty members, often champions of the cause who had prior Peace Corps or other experience in developing countries. They were motivated in part by the educational liberation philosophy of Paulo Freire (1970) who viewed teachers and students as learning together and focusing primarily on outcomes of education such as development for the masses and distribution of benefits of farming and food systems.

Challenges of teaching sustainable agriculture and agroecology in landgrant universities have been explored (Altieri and Francis, 1992). There are defined courses needed for an undergraduate degree in agriculture, and many instructors maintain that credits taken in integrative systems take away opportunities for more in-depth preparation in specific disciplines such as agronomy, entomology, plant pathology, economics, or engineering. Innovative educators and curriculum planners now accept the value of systems thinking as provided in these integrative courses, and more offerings are appearing in public and private universities (Francis, 2009). A systems approach to study across disciplines will provide students with important competencies they will need to deal with complexity and uncertainty in the future.

II. TRANSDISCIPLINARY EDUCATION IN AN ECO-SOCIAL SYSTEM

Conventional wisdom in the U.S. landgrant system maintains that both research and teaching are enhanced by a close link between them. The strategy of split appointments, with researchers actively working on contemporary issues and bringing the latest results to the classroom, has pervaded our thinking. Linking research with teaching and learning can be valued in undergraduate courses on sustainability if the research is continually viewed in the context of whole systems; the link could be detrimental to learning if the successful researcher in component science has difficulty emerging from that specialty to provide a systems perspective on applications to critical issues. In the landgrant system, split appointments can present an acute problem if major rewards are based on research publications and grant success. One review concludes that most research evidence does not find a positive correlation between success in research and success in teaching (e.g., Hattie and Marsh, 1996; 2002; Jenkins *et al*., 2003). Organization of most universities includes separate budgets, assignments, and facilities for the two activities, even though faculty have split appointments (Barnett, 2005). Lieblein *et al*. (2000b) provide three models of university structure, including a conventional model and two futuristic alternatives that depend on teams doing experiential learning on farms and in communities.

A workshop of the European Network of Organic Agriculture Teachers (ENOAT) in Italy explored the challenges and potentials of the interaction of teaching and research in agroecology and organic farming (Caporali *et al*., 2007). There was strong agreement about the importance of working across disciplinary lines as the only rational way to deal with broad and complex issues. We recognized *multidisciplinary* as an approach that brings together multiple disciplines, but does not guarantee an integration of perspectives or research methods, nor any emergent value of the process. There is not necessarily an equal sharing of the parts (Schunn *et al*., 1998). *Interdisciplinary* strategies are important to address problems that "escape the confines of a single discipline" (Mittelstrass, 1998), yet leave the impression that they deal primarily with the issues that would otherwise fall through the cracks between specialties. *Transdisciplinary* is a term of choice because it concerns "that which is at once between the disciplines, across the different disciplines, and beyond all disciplines. Its goal is the understanding of the present world, of which one of the imperatives is the unity of knowledge" (Basarab, 2002).

Competency in agroecology requires skills that go beyond what is available in any one department or specialization. Challenges in agricultural and food systems involve use of natural resources, complicated farming practices, economics in a time of uncertainty, environmental impacts, and social implications of decisions in these human activity systems. Lieblein and Francis (2007a) provide a review of literature on linkages between research and teaching, ways to bridge what is often envisioned as a gap, and a proposed "learning umbrella" that covers both activities (Brew and Boud, 1995). The cases we present later describe relevant examples of research-based educational activities that contribute to systems competencies.

III. AGROECOLOGY AS A FOUNDATION FOR SUSTAINABLE AGRICULTURE

A. Emergence of an Integrative Ecology of Food Systems: Agroecology

Societal demands on agriculture are mounting and becoming more complex. In addition to major increases in global food production in coming decades, society increasingly expects rural landscapes to provide a wide range of other goods, services and amenities. These include biofuels, bio-industrial products (Eaglesham, 2006) and environmental services such as carbon storage, biodiversity conservation, aquifer recharge (Boody *et al*., 2005; Jordan *et al*., 2007), and the construction of resilient land-use systems to manage risks from climate change (Berkes, 2007). The challenge is to increase production of marketable commodities, while maintaining integrity of essential life-support functions of the biosphere. More broadly, the challenge is to better design and manage the interconnections between agriculture and basic life-support systems of society: food, water, energy and land-use systems. Such demands must be met within the context of global environmental change, especially greater climate instability. The intertwined issues of production, conservation and adaptation constitute one of our grand challenges facing humanity. It will be necessary to substantially redesign agricultural systems and their interface with food, water, energy and land-use systems (Francis and Porter, 2010).

Any redesign will be complex and contested, involving difficulties aptly described as 'wicked' problems (Batie, 2008). In these situations, different parties view and define the problem quite differently, depending on their particular worldviews, values, and vested interests. Wicked problems typically entail high levels of uncertainty and large 'decision stakes' (i.e., large public risks and/or opportunities are involved). They are marked by strong controversy, stakes are high, the facts of the situation are uncertain, and intense debate occurs among stakeholders holding wide-ranging views on what constitutes sustainable and responsible development in social, economic, and environmental terms (Jordan *et al*., 2008). Wicked problems in agriculture are also biocomplex, meaning that production, conservation and adaptation are affected by the interplay of biophysical and social factors that are spatially, organizationally and historically complex (Cottingham, 2002; Pickett *et al*., 2005).

How should society organize itself in response to wicked problems in agriculture and interconnected food, energy, water and land-use systems? Sustainability science (Clark, 2006) is providing a rallying point for many efforts to answer this question. This field views the interplay of social and biophysical factors as the genesis of wicked problems. To make progress, sustainability science aims to create new understanding by close coupling of multiple knowledge systems into 'learning systems' based on social networks (Ison *et al.*, 2007). Making durable improvements in the face of wicked problems requires multiple rationalities, including intellectual, practical, spiritual, emotional, ethical, and aesthetic. To meet these needs, natural and social scientists must engage with broader knowledge systems and learning/action networks, by involving heterogeneous groups of stakeholders. When learning and action are effectively integrated, stakeholder groups can take concerted and coordinated action (Magerum, 2002; Pahl-Wostl and Hare, 2004; Steyaert *et al.*, 2007; Mandarano, 2008) that can contribute to progress in the face of wicked problems in managed ecosystems.

Motivated by hope of better addressing wicked problems and by emerging tenets of sustainability science, the discipline of agroecology has recently shifted strongly toward a more integrative mode (Flora, 2001; Uphoff, 2002; Dalgaard *et al*., 2003; Francis *et al.*, 2003; Jordan *et al.*, 2005a; 2008; Robertson *et al*., 2008; Warner, 2008; Francis *et al*., 2008). Wezel *et al*. (2009) found that contemporary usage of 'agroecology' reveals a range of non-exclusive meanings, variously describing a *science*, a *practice*, and/or a popular *movement* as applied in Germany, France, Brazil, the United States and elsewhere. Agroecology initially was used to describe and analyze production-related issues in farming systems via natural science, combining the perspectives of agronomy and agriculture with ecology. This conception of agroecology-as-science persists today in a number of countries including France and the United States.

B. Broadening Agroecology to Include Food Systems

The concept of agroecology has been broadened substantially to include environmental, economic, social, political, and ethical dimensions. Academics in the Nordic Region and the U.S. Midwest now define agroecology as *the ecology of food systems* (Francis *et al*., 2003). This definition may need additional revision to reflect societal demands that agriculture produce a range of non-food goods, services and amenities. Wezel *et al*. (2009) contend that a more expansive use of the term emerged in the 1970s with agroecology seen as both a set of practical applications and a movement. This activity was partly in response to the concerns about unexpected consequences of the highly successful Green Revolution in developing countries, such as environmental impacts of substantial increases in chemical fertilizer and pesticide use, and high-tech/high-yield strategies that often ignored social structure and distribution of benefits.

Agroecology has potential to embrace a broad, complex, interacting set of biophysical and socioeconomic dimensions of food systems. Beyond opening unique vistas for research, there is an exciting array of applications in experiential learning as illustrated by the case studies described later. Integrative qualities emerge that can enhance the value of research and education. For example, there is focus on long-term, place-based, comparative research and development projects (Carpenter *et al.*, 2009) using tools such as foodshed analysis (Peters *et al.*, 2009) and life cycle analysis (Hendrickson *et al.*, 2006), and such ecological concepts as hierarchy of scale, system boundaries, and evaluation of biodiversity and nutrient cycles. There is also potential for integration of multiple natural and social-scientific methods such as multi-scale empirical work, modeling, simulation and adaptive experimentation (Cook *et al*., 2004), and analyses that integrate patterns and processes across a wide range of spatiotemporal scales such as competition and mutualism, biogeochemical cycles, and biological and social succession.

These same concepts and principles can inform the design of ‘learning landscapes’ in which students are introduced to the complexities and uncertainty of farming and food systems in the present and their design for the future. We have found that students who study to become agroecologists through applied systems courses in the Nordic Region gain an appreciation of how to deal with complicated and multi-dimensional situations (Lieblein *et al*., 2004). In design of educational strategies, we have focused on the learner, on sharing responsibility for education, and on students taking an active role in a process that can lead to capacity for responsible action (Lieblein and Francis, 2007b). It is the evolution of agroecology from a singular focus on science, to an incorporation of practical applications, to creation of movements in several countries that has enriched this area of study. To pursue a broad strategy of experiential learning in agriculture and food systems, we have found a need for different types of activities, including modifications in practical learning through case studies.

C. Open-Ended Case Studies: A Primary Learning Strategy

One key method for education in agroecology that has proven valuable for systems learning is the open-ended case study (Francis *et al.*, 2009). One prerequisite for learning is to generate enthusiasm around a topic and another to create linkages to prior experience (Dewey, 1916). The decision case method has been used by many educators to meet these needs, but the majority of such cases are “closed” in that they present situations in which the solution is already known to instructor and client (American Society of Agronomy, 2006). The open-ended cases we use in agorecology are distinct in their process of joint exploration by students, instructors, and clients of complex real-life situations where often neither the relevant questions nor the answers have yet been identified (Francis *et al*., 2009). The open case method is further characterized by introducing students to a discovery approach to learning, to the need for digging out relevant information on a farm or in a community, to develop potential future scenarios rather than providing one discrete solution, and to elaborate a series of criteria for evaluating success of the scenarios.

Compared to conventional decision cases, the open-ended case study strategy places primary emphasis on co-learning by students, instructors, and clients (Francis *et al*., 2009). The goal of seeking information in the field from farmer or community key clients is to develop a rich picture of the current situation, and to establish as much as possible the long-term goals of farmer or community and what they would like to achieve within a certain time frame. This depends on the natural resource and economic base, and also on individual and social capital in that place and the philosophies and world views of the participants. There is an open co-learning atmosphere where everyone is a player in defining the issues and seeking alternative solutions for the future. Multiple sources of information and stimulation feed into continuous interaction among the players. In Norway, student teams are working with farmers and communities that have a goal to increase organic food consumption. The projects are taking “action research” to a new level of accountability, yet there is a safe space under the learning umbrella to venture broadly and take risks that would not be encouraged in a conventional class setting.

IV. CASE STUDIES IN EXPERIENTIAL SYSTEMS LEARNING

A. Norway: UMB Agroecology Courses with Open-ended Cases

For the past decade, the autumn courses at the Norwegian University of Life Sciences (UMB) have provided study opportunities in food and farming systems using the open-ended case strategy. Based on concepts developed in one-week Ph.D. courses on systems research in the mid-1990s (Lieblein *et al*., 1999), the semester includes an experiential learning component on farms and in rural communities in Norway. Design of the initial courses was informed by an in-depth evaluation in a workshop of former faculty and student participants (Lieblein *et al*., 2000a). We have observed that the inclusiveness and transparency in planning and implementation of courses have been valuable as a way to involve people from the Nordic Region and to help in recruiting students.

At the heart of the semester are open-ended case studies that explore contemporary challenges facing farmers and current issues in food systems in Norwegian communities. As we explain to students, the cases have not yet been solved. We work together as a team of students/faculty/clients to create a rich picture of the situation, the goals of farmer and community, and the resources available. Student teams identify the key issues, and then design a series of potential scenarios that could be used by farmer or community to address them (Francis *et al.*, 2009). This is quite different from students doing a decision case where they must be clever enough to find out what the instructor and client already know. Based on field visits, observations, and interviews, students consider multiple ways of analyzing the current system and then design scenarios toward a desired future situation that will help clients meet their goals. Teams produce client documents for their key contacts in the field, and individual students prepare learning documents that summarize their personal experiences in learning. We now collaborate with a national program seeking to help Norway reach its stated goal of 15% organic food production and consumption by 2020. The *Økoløft* program funds half the cost of team visits to communities, and this raises the level of responsibility and accountability for everyone in the project.

Scenario building and evaluation of impacts are representative of the steps up toward visioning and action that are encompassed in the external learning ladder conceptualized in this program (Lieblein *et al*., 2007). The open-ended case study strategy is integral to *becoming an agroecologist* and systems thinker, well prepared to deal with complexity and with rapidly changing situations (Lieblein *et al.*, 2004). Agroecology courses prepare students to make meaningful contributions to the food system through responsible action in the future (Lieblein and Francis, 2007b). In a sense, students are working on real-world issues in real time, and are gathering information as it is needed in this "just-in-time" learning environment (Salomonsson *et al*., 2005).

B. U.S.: Midwest Agroecosystems Analysis Course

Since 1998, a summer experiential learning course to develop competencies in agroecosystems analysis has been held each year in Iowa, Minnesota, and Nebraska (Wiedenhoeft *et al.*, 2003). The goals are to give students first-hand experience in the dominant maize-soybean and confined livestock plus alternative farming systems in the region, and to provide tools for collecting information, analyzing, and evaluating the sustainability of different farms. Students focus on production, economics, environmental impact, and social viability of each operation, and learn to use various biological and social science methods (Rickerl and Francis, 2004). Provided with references ahead of the field visits and practice with interview skills and farm models, students then are given broad leeway in how they organize their interviews, design analyses, and summarize results in oral and written presentations. The instructors consider this freedom to make decisions as one key to developing competence as autonomous learners.

The course begins on the southern edge of the Des Moines lobe formed during the latest glacial period, with discussions about glacial formation, movement, and recession. Consequences for the landscape and soils, and how the climax northern tall grass prairie impacts potential for agriculture are explored, as students walk through a field never plowed, one piece of the 0.01% of this Iowa ecosystem that remains (Samson and Knopf, 1994), Most people including those involved in agriculture do not recognize prairie. The current state of northern tallgrass prairie conservation is reviewed and participants are introduced to the most conspicuous prairie plants and encouraged to explore on their own and get a feel for the ecosystem. In a group discussion participants share what they have seen and felt, and consider how 'prairie wisdom' might be put to work in contemporary food production systems. The prairie ecosystem then is identified as one standard by which environmental sustainability and farming systems resilience in the region can be evaluated. One student said, "I think the prairie misses the bison."

The class visits eight farms, delving into farmers' philosophies and goals, natural resource and economic endowments, and current systems with their successes and challenges. Based on this experience and evaluation, they envision potential future scenarios. Students are urged to develop meaningful questions and envision alternative future directions that would better help each farmer achieve their goals. The emphasis is on system resilience and sustainability, on potential of the farmer and family to flourish even in times of uncertainty and economic change, and on dealing with complexity through application of ecological principles in design of farming systems. In the study of systems, students look at issues across hierarchies of scale and time. They explore the intricate interactions among components and the emergent properties of systems, and as much as possible attempt to take a holistic and systemic view of the overall operation of the farm within the landscape and local community context. The result has been a revelation to those students who are accustomed to learning in specific disciplines, at times with information that is context free, and who have been told specifically what they are supposed to learn. The open-ended case study approach has proven valuable for learning and building systems competencies.

Evaluation of learning in the agroecosystems analysis course has been multidimensional, using daily individual surveys of students and faculty, frequent reflection sessions, careful instructor reading of students' individual learner documents submitted at the end of the course, peer evaluations within groups, faculty observations of students in the field and in group work, and follow-through surveys and interviews after the course is finished. From these sources, Harms *et al*. (2009) have identified five causal conditions that are influential in creating learning and the conditions that would encourage behavioral change in students: hands-on experience, emotional response, human interaction, self-efficacy, and intensity of experience. They found additional conditions that need to be considered to improve the learning situation: length of course, appropriateness and rigor of curriculum, learner-centered activities, ongoing education, and metacognitive processes.

C. U.S.: Integrative Agroecology

Ecology of Agricultural Systems is a course at University of Minnesota-Twin Cities which prepares students to design and manage the interconnections between agriculture and basic life-support systems of society: food, water, energy, and land use. Design and management must interweave production, conservation and continuous adaptation to change at many scales, and presents practitioners with many 'wicked' problems (Batie, 2008), those in which different parties view and define problems quite differently. There may be strong controversy and biocomplexity, in which production, conservation and adaptation are affected by the interplay of biophysical and social factors that are spatially, organizationally and historically complex.

The premise of *Ecology of Agricultural Systems* is that difficult problems in agriculture must be addressed by a novel and emerging discipline, termed 'integrative agroecology,' itself a realization of a new 'meta-discipline' of sustainability science (Clark, 2006). Agriculture and related food, water, energy and land-use systems are understood as coupled human-natural systems (CHNS) (Liu *et al*., 2007). Such coupling creates potential for strong and rapid feedback dynamics, with coupled 'eco-social' interactions in CHNS that are fundamental to integrative agroecology.

Ecology of Agricultural Systems was designed to provide useful concepts for viewing agriculture through the lens of integrative agroecology, use practical experiences, and encourage reflection on concepts and practice. Because integrative agroecology is new, we emphasize methods of agroecological analysis and the development of mental models and perspectives, such as an ability to perceive wicked problems in agriculture and their relationships with systems of food, energy, water and land-use. To do this, the course offers experience in applying methods for systems thinking to complex agricultural issues. We organize model-making and other activities to practice 'systemicity' around two focal notions. *Landscapes* are the land areas containing multiple ecosystems that are distinct in structure and function. *Management regimes* are the multiple agencies, organizations and institutions from different social sectors (technological, financial, commercial, regulatory, physical and biological infrastructure) that interact to govern resource and production systems. Students develop and evaluate their models and other course concepts in a semester-long project that features 'community-based learning' (CBL), also known as service learning (Jordan *et al.*, 2005). They are engaged with partner organizations that provide a practical application for the work.

D. Sweden: Swedish Test Pilots

A unique experiment was launched at the Swedish University of Agricultural Sciences (SLU) in Uppsala where a number of crop science students were not satisfied with their current curriculum, immersed in chemistry and molecular biology, and were seeking more relevance in education. With an expectation to learn about agriculture as a human driven activity in its socio-economic and ecological context, students found that crop science courses did not provide this breadth of focus. Three students chose to plan their own systems studies, first in Sweden and later in Viet Nam. They embraced the concept of experiential learning and took on the responsibility for planning their own systems research and learning experiences. In the first eight weeks they made multiple farm visits and conducted in-depth interviews of farmers on two farms, one conventional and one organic, in the fertile valley north of Uppsala. They explored the inputs and outputs from the farms; beyond the farm boundaries they looked at the complexity of the food system after harvest in the processing and marketing of products from the farms. An integrated report of the study was presented to their advisor and to the farmers.

Concerned that they were not stretching their comfort zones with this study in Sweden, the group decided to travel to Viet Nam to study farming systems and marketing at a local university and then conduct action research in the field. After substantial reading and preparation, they spent two weeks in seminar-type sessions on the campus of Hue University, in cooperation with a masters program project with SLU and Vietnamese universities [the RDViet Project, http://www.rdviet.net/] doing systems analysis study together with local college students. Supervised by teachers from An Giang University, they spent a week in field studies in two villages with rice production as the primary economic activity. One was an ethnic Vietnamese village and the other a Khmer village. To explore the impacts of globalization on the decisions of farmers in these two contrasting places, students conducted interviews with relatively wealthy farmers, average farmers, and poor farmers, as well as with a focus group of decision makers in each community. Through translators, they examined the impacts of recent growth of export markets for Viet Nam on the apparent financial success and well-being of these farmers and families. This was a tremendous experience for the students, and they prepared a report on the adventure that was published by their department at SLU (Palmer *et al*., 2008). In addition, the process of developing the concept and carrying out the research/education project was summarized and published in an education journal with the students and instructors as co-authors (Salomonsson *et al.*, 2008). This model is seen as a potential future type of class for highly motivated students who want to take responsibility for their own systems education, and to do this outside the intellectual and physical confines of the university classroom and department structure.

E. U.S.: African Agroecology Systems Evaluation through Adventure Learning

In spring semester 2009, students at University of Minnesota participated in an adventure learning course in agroecology where the instructor (Paul Porter) planned to travel over a four-month period from Cairo, Egypt to Cape Town, South Africa by bicycle, reporting on the agroecosystems and food he encountered each day. Adventure learning (AL) is a hybrid distance education approach that provides students with opportunities to explore real-world issues through authentic learning experiences within collaborative learning environments (Doering, 2006).

"Food and Agriculture from Cairo to Cape Town at 10 mph," provided students with an introduction to food, agriculture and agroecosystems in 10 African countries (Egypt, Sudan, Ethiopia, Kenya, Tanzania, Malawi, Zambia, Botswana, Namibia, and South Africa). The instructor traveled by bicycle over 6000 kilometers through five countries until a bicycling accident in southern Tanzania cut short his travel, but not the course. Students continued to follow the bicycling group until they arrived in Cape Town.

Co-taught by a teaching assistant, the course utilized faculty guest speakers, student group presentations and related readings from a wide array of disciplines, from climatology and culture to social and agronomic sciences. With satellite phone technology and the internet, the instructor provided daily written and audio-blogs of his experiences, focusing on food, agriculture, and agroecosystems. Each day he would travel about 120 kilometers, and report on the ecology of farming and food systems he encountered. Discussion ranged from topics on false banana, t'ef and cultivating with livestock on terraces to challenges of nomadic herdsmen and the constant quest for water. Relationships among climate, soil, elevation and latitude were discussed relative to historic and current cropping practices. Well over 100 plant and animal species were discussed, far more diverse than what typical U.S. students find in the Midwest.

There was no textbook for the course. Assigned readings included peer reviewed articles, current events, development reports and daily blogs posted by the instructor <http://paulporter.wordpress.com>. The course was offered as a general elective for undergraduates as well as to honors students and graduate students; 34 students from five colleges representing 13 majors enrolled in the three-credit course. In their course evaluations, the students expressed a sense of 'being there' and experiencing crossing deserts in the heat on rough roads, surviving thin air and seeing cool season crops at higher elevations, as well as the transition from barren dry environments to biologically diverse intercropped landscapes. Building from lessons learned, a similar course was conducted in 2010, when the instructor completed the agroecology journey through Africa. This creative type of educational experience enhances the breadth of learning opportunities to which the students are exposed and provides a model for developing new competencies through distance education.

F. U.S.: Learning Communities

In higher education, curricular learning communities offer a common cohort of students the opportunity to build community while enrolled in classes that are linked or clustered during an academic term, often around an interdisciplinary theme. Recognizing that learning is a social endeavor, the goal of learning communities is to impact student learning by creating purposeful groupings of students. At Iowa State University this approach has been used to help students make the transition from high school to university, to increase retention of students, to encourage greater student engagement academically and socially, and to stimulate greater success in learning. The students take similar classes, as well as linked classes, i.e., English composition classes linked to discipline content classes (Wiedenhoeft and Loynachan, 2009). The community idea organizes students into groups to provide a smaller college atmosphere within the large landgrant university.

In 1998 and 1999, three groups of 12 first-year agronomy students were organized; two of the groups were in learning communities, while the third group was not (Pogranichniy *et al*., 2001). All three groups enrolled in the same required courses. The learning community groups were given an additional two-day field trip, as well as weekly special seminar sessions on time management, appreciation of different learning styles, study and testing skills, and opportunities for career exploration. There was greater faculty/staff involvement with the community groups, including peer mentors, faculty mentors and a staff coordinator. After two years of this experience, faculty reported that the program had "some limited success." Those students participating in the learning communities had a quicker adjustment from high school to the university learning environment, a small but significant increase in academic performance as measured by grade point average, and a slightly higher level of student retention. What was important to faculty involved in the communities was the qualitative observation that students were better adjusted to the university. This was enough to justify continuing the program, and today this is an integral option for undergraduate students at Iowa State University (Wiedenhoeft and Loynachan, 2009).

G. Nordic Region: On-Line Course in Agroecology

Since 2004 a fully web-based course in agroecology has been offered globally by instructors from four Nordic universities (Lieblein *et al*., 2005). To build competencies, the course offers an introduction to the systems approach and complements specific courses students have taken in other disciplines. Instructors introduce an experiential learning approach in which dialogue between the 'real world' and the 'abstract' (Kolb, 1984) can be used in a distance learning situation. Using Kolb's learning cycle with an example from the real world, we developed a case based on a Danish organic dairy farm. With quantitative farm data as well as qualitative information from interviews with the farmer and his family, the case is the focal point of student work through the course.

Course activities followed the Kolb's cycle, pulling in theoretical background and the tools needed along the way. An initial question is, What is on the farm and how does the farm function? Theory is introduced through readings on systems thinking and agroecology, as well as mind-mapping and other tools. Later questions focus on goal conflicts and the tasks of making sound recommendations to the farmer. This approach calls for students to put themselves into the roles of different players, including farmer and advisor. Students work both in groups and individually and keep learning logs through the course to ensure reflection on their own learning.

Instructors had a long history of collaboration in adopting student-centered and experiential approaches, yet the development and implementation of this distance course was a new learning experience for all. Teachers represent a wide range of disciplines within agriculture, food science, and veterinary medicine. Facilitating a learning process on the farming system level puts less emphasis on each specific field of expertise, thus instructors need the courage to move out of their comfort zones in dealing with students and the material, as well as opening the potential of an innovative learning approach.

Challenges that are addressed during the course relate to cultural and geographical differences among the students. Like most international groups, students enter the course not only with a diverse set of knowledge and experiences, but also with large differences in their attitudes toward learning, authorities, and group work. Since the course started we have revised the material annually, changing the readings, including emerging discussions on multifunctional agriculture, and changing some of the tools offered, such as SWOT and Force Field analysis. Taking into account the increasing student numbers from the South we plan to expand the applied component with a case from the developing world, giving students from all backgrounds the opportunity to work with different contexts and expand their agroecology competencies.

V. FUTURE LEARNING LANDSCAPES: AGROECOLOGY AND EXPERIENTIAL EDUCATION

Despite increasing calls for graduate training in integrative agroecology (Francis *et al*., 2008), efforts to develop more programs that draw on the conceptual developments outlined in the introduction have been limited. Some programs in sustainability science, land-change science, and new critical understanding of participatory approaches are being tested (Bawden, 2007b; Ison *et al*., 2007; Jordan *et al*., 2008). Excellent graduate programs address sustainable agriculture (e.g., Iowa State Univ. http://www.sust.ag.iastate.edu) but we are not aware of graduate programs that address the broader challenge of applying the emerging frameworks of biocomplexity, sustainability science, and land-change science to create an integrative agroecology framework. Relevant systems education programs are emerging in the Nordic region (e.g., Nordic School of Agroecology, www.agroasis.org). Useful insights come from frameworks created by graduate curricula in sustainability science in a range of physical sciences and ecological sciences (Francis *et al*., 2008). Recent start-up programs include the School of Sustainability at Arizona State University (http://schoolofsustainability.asu.edu) and the Resilience and Adaptation Program at University of Alaska (http://www.rap.uaf.edu).

A fundamental premise is that our students will be involved in the development of new systems of governance, or new management regimes to better manage interconnections between agriculture and overarching resource systems of food, energy, water and land-use. Network forms of governance can enable effective co-management—coordinated, concerted and collective action across multiple social, economic, political sectors and scales. We view these network governance mechanisms as a necessary complement and counterweight to regulatory and market forces (Ison *et al*., 2007). To become effective agroecologists, our students must develop a set of perspectives, habits of minds and behavioral competencies that will enable them to participate in network governance and co-management. Among these abilities, new capacities for communicative and systemic learning are particularly important. Crucial outcomes are well summarized in a rubric—the ‘Five Cs’—recently articulated by Richard Bawden, a seminal figure in agroecology education (Bawden, 2007b; Jordan *et al*., 2008). The ‘Five Cs’ are both key attributes of the wicked problems that new management regimes must address and related competencies that must be developed to enable students to become agroecologists capable of facing wicked challenges. These attributes and related competencies are:

- *Contestability*, requiring competencies for engaging productively with differences in worldview, values, and interests among multiple stakeholders in wicked problems,
- *Contingency*, requiring competencies for dealing with unpredictable futures in agricultural systems beset by difficult problems rooted in biocomplexity,
- *Collectivity*, requiring competencies in social learning for collective action,
- *Connectivity*, requiring competencies in methods for systemic understanding,
- *Cognition*, mental models, habits of mind and worldviews are powerful factors in wicked problems, strongly affecting understanding and action of interested parties; agroecologists need competencies for critical understanding of cognition and learning—individual and collective—to deal with future complexity.

Communicative learning is applied in the Habermas/Mezirow sense (Mezirow, 1996) as a process that helps us understand how others see the world, in terms of theoretical validity, normative correctness and honesty of views. This learning increases understanding of the meaning and significance of statements and actions in a group of interacting stakeholders. The outcome is increased capacity for communication and deliberation, enabling increases in mutual understanding, collaborative learning, and collective action (Bawden, 2007a; Jordan *et al*., 2008). Such learning creates a critically important basis for co-management and increased social capital, including trust, willingness to cooperate, and shared norms and values. Systemic learning is also fundamental, because agriculture and related resource systems are seen as coupled human-natural systems, and to understand them requires students to learn and practice systems thinking. Systemic learning refers to understanding the holistic nature of agriculture, with all its complexities and interactions (Bawden, 2007b). Systemic learning involves inquiry and analysis on three interrelated levels: systems, sub-systems, and super-systems (Jordan *et al*., 2005). Finally, communicative and systemic learning can be integrated via the formation of 'critical learning systems' (CLS) (Bawden, 2005), which are comprised of social actors (individuals, organizations, institutions) that share a common interest in an agroecosystem. Ability to apply these concepts is an important competency for agroecologists.

Drawing on these new theories and experiences in the literature, we are building on the early concepts of Dewey (1916) and other visionaries, and we are applying the theory to courses in the Nordic Region and the U.S. Midwest to improve the learning landscape. Instructors in these courses understand the links that provide an efficient transfer of relevant experience and information from the research laboratory, experimental field, and rural community into the classroom. We recognize the value of student research and class projects as important sources of ideas that we can use to deal with contemporary challenges in farming and food systems. We believe that experiential learning is an effective means to achieve education for students concerned about responsible action, and these are the people who are going to make a difference in the world and the human condition. Our focus is on building competencies in agroecologists, by designing coherent curricula or learning landscapes that transcend the intrinsic limitations of individual courses that are often narrow learning experiences of limited scope and duration.

In such a learning landscape, we help students develop the competencies listed above to participate in CLS, and also the underlying capacities for communicative and systemic learning. For example, we believe that agricultural scientists concerned with such challenges need capacity for intellectually rigorous foresight (Tonn *et al*., 2000), using such techniques as scenario planning and facilitated modeling (Kallis *et al*., 2006). They also need holistic approaches suited to more immediate challenges, such as soft-systems methodology (Jordan *et al*., 2005), and social multi-criteria analysis or adaptive co-management (Olsson *et al*., 2007; Berkes, 2007) or skill in the creation and use of boundary objects (Steyaert, 2007) such as texts and graphics. These convey information about social or biophysical attributes of an agroecosystem and serve to facilitate critical systems thinking by a multi-stakeholder group, for example a terrain-analysis map depicting areas vulnerable to soil erosion. Established and emerging methods for communicative and systemic learning are the key features of agroecology curricula, leading to new ways of seeing and corresponding ways of doing.

From case studies, from experiences of the past decade, and from recent conceptual developments, we can draw out a number of key elements and conclusions:

- learning is a social as well as an individual process, and there is a continuing need to explore the best ways to enhance effective team project work,
- knowledge, skills, competencies, and attitudes must go beyond technical details; ability to work in groups, capacity to see the larger picture, experience in communication with the public, and broad capacity to deal with uncertainty, risk and change are essential,
- experiential learning means getting into the field and the community, working with clients to understand their goals and local context, and appreciating uniqueness of place and specificity of solutions to location-specific individual and group challenges,
- methods of service- and community-based learning provide useful guidelines, in principle and practice, for such community-engaged learning,
- transdisciplinary team teaching is crucial to the broad goals of learning about systems; there are biophysical, economic, social and political dimensions in contemporary problems, important in developing resilient and sustainable alternatives,
- frequent and meaningful interactions among the instructors have been essential to applying broad concepts, guiding students through learning landscapes, and evaluation,
- bringing together natural resource and biodiversity questions with those in agricultural production, farm and regional economics, complex social realities, and political dimensions involve developing different types of practical models to help students understand complexity, and require methods from both biophysical and social sciences,
- methods for integrative analyses are hardly well defined in the domain of agroecology research, and practical pedagogical models are very much a work-in-progress,
- evaluation is an integral and continuing part of design and implementation of experiential learning activities and programs, and frequent modification along the way through educational adaptive management has been important to success,
- recognizing the intensity of instructor involvement in this type of learning environment is important, as administrators and peer evaluators look at credit hour accumulation as the key indicator of educational "success" in today's tight economic times; we need to seek resource-efficient alternatives to achieve the same goals without excessive investment of faculty time and university resources.

Major areas for future development include the application of methods for systemic and communicative learning to agroecological curricula.. This is especially important for undergraduate curricula, as these students are conditioned to rote learning and may be at stages of cognitive development that create significant impediments to systemic and communicative learning (Salner, 1986). Techniques such as soft-systems methodology are considered to be difficult to teach to undergraduates. Also needed are opportunities for critical self-reflection, for example meta-cognition and epistemic cognition, particularly on the basis of experiences that engage students for reasonably long periods. These are opportunities to apply and evaluate methods for communicative and systemic learning, effective functioning in a critical learning system, and participation in co-management. We conclude that agroecology provides the framework and the methods for effective systems education, based on transdisciplinary research, which can shape our future learning landscapes and develop compentencies needed for responsible action by agroecologists.

REFERENCES

Altieri, M. A. 1983. *Agroecology*. Univ. California Press, Berkeley, California.

Altieri, M. A., and Francis, C. A. 1992. Incorporating agroecology into the conventional agricultural curriculum. *Amer. J. Altern. Agric*. **7:** 89–93.

American Society of Agronomy. 2006. *Case Studies Published in Journal of Natural Resources and Life Sciences Education, 1992–2005*. Amer. Soc. Agron., Madison, Wisconsin.

Barnett, R. (Ed.). 2005. *Reshaping the University: New Relationships Between Research, Scholarship, and Teaching*. McGraw Hill/Open Univ. Press, Maidenhead, U.K.

Basarab, N. 2002. *Manifesto of Transdisciplinarity*. State Univ. New York Press, Albany, New York.

Batie, S. 2008. Sustainability science: Statement of the Friiberg workshop on sustainability Science. *Amer. J. Agri. Econ.* **90:** 1176–1191.

Bawden, R. J. 1991. Systems thinking and practice in agriculture. *J. Dairy Sci*. **74:** 2362–2373.

Bawden, R. J. 2005. Systemic development at Hawkesbury: Some personal lessons from experience. *Sys. Res. Behav. Sci.* **22:** 151–164.

Bawden, R. J. 2007a. Knowing systems and the environment. **In**: *Sage Handbook on Environment and Society.* pp. 224–234. Pretty, J., Ball, A., Benton, T., Guivant, J., Lee, D. R., Orr, D., Pfeffer, M. and Ward, H., Eds. Sage Publ., London.

Bawden, R. J. 2007b. Pedagogies for persistence: Cognitive challenges and collective competencies. *Intl. J. Sustain. Devel. Innovation* **2:** 299–314.

Berkes, F. 2007. Understanding uncertainty and reducing vulnerability: Lessons from resilience thinking. *Natural Hazards* **41:** 283–295.

Boody, G., Vondracek, B., Andow, D. A., Krinke, M., Westra, J., Zimmerman, J., and Welle, P. 2005. Multifunctional agriculture in the United States. *Bioscience* **55:** 27–38.

Brew, A., and Baud, D. 1995.Teaching and research: establishing the vital link with learning. *Higher Educ.* **29:** 261–273,

Caporali, F., Lieblein, G., von Fragstein, P., and Francis, C. (Eds.). 2007. *Teaching and Research in Agroecology and Organic Farming: Challenges and Perspectives*. Proceedings European Network of Organic Agriculture Teachers (ENOAT). Pieve Tesino (TN), Italy, Aug. 29–Sep. 2.

Carpenter, S. R., Mooney, H. A., Agard, J., Capistrano, D., DeFries, R. S., Diaz, S., Dietz, T., Duraiappah, A. K., Oteng-Yeboah, A., Pereira, H. M., Perrings, C., Reid, W. V., Sarukhan, J., Scholes, R. J., and Whyte, A. 2009. Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proc. Nat. Acad. Sci*. **106:** 1305–1312.

Checkland, P. B. 1981. *Systems Thinking, Systems Practice*. John Wiley, New York.

Checkland, P. B., and Scholes, J. 1990. *Soft Systems Methodology in Action*. John Wiley, Chichester, U.K.

Clark, W. C. 2006. Sustainability science: A room of its own. *Proc. Nat. Acad. Sci*. **104:** 1737–1738.

Cook, W. M., Casagrande, D. G., Hope, D., Groffman, P. M., and Collins, S. L. 2004. Learning to roll with the punches: Adaptive experimentation in human-dominated systems. *Frontiers Ecol. Environ*. **2:** 467–474.

Cottingham, K. L. 2002. Tackling biocomplexity: The role of people, tools, and scale. *Bioscience* **52:** 793–799.

Daily, G. C. (Ed.). 1997. *Nature's Services: Societal Dependence on Natural Ecosystems.* Island Press, Washington, D.C.

Dalgaard, T., Hutchings, N. J., and Porter, J. R. 2003. Agroecology, scaling and interdisciplinarity. *Agric. Ecosys. & Environ*. **100:** 39–51.

Dewey, J. 1916. *Democracy and Education: An Introduction to* The Philosophy of Education, *1966 Edition.* Free Press, New York.

Doering, A. 2006. Adventure learning: Transformative hybrid online education. *Distance Education* **27:** 197–215.

Eaglesham, A. 2006. *Summary Proceedings: Third Annual World Congress on Industrial Biotechnology and Bioprocessing*. 11–14 July 2006, Toronto, Canada. nabc.cals.cornell.edu/pubs/WCIBB2006_proc.pdf. Accessed on 23 June 2009.

Flora, C.B. 2001. Shifting agroecosystems and communities, **In**: *Interactions Between Agroecosystems and Rural Communities*. pp. 5–14. Flora, C.B. Ed., CRC Press, Boca Raton, Florida.

Francis, C. A. 2009. Education in organic farming and food systems. **In**: *Organic Farming: The Ecological System.* pp. 283–300. Francis, C. A., Ed., Agron. Monograph 54, Amer. Soc. Agron., Madison, Wisconsin.

Francis, C., King, J., Lieblein, G., Breland, T. A., Salomonsson, L., Sriskandarajah, N., Porter, P., and Wiedenhoeft, M. 2009. Open-ended cases in agroecology: Farming and food systems in the Nordic Region and the U.S. Midwest. *J. Agric. Educ. & Extension* **15:** 385–400.

Francis, C., Lieblein, G., Breland, T. A., Salomonsson, L., Geber, U., Sriskandarajah, N., and Langer, V. 2008. Transdisciplinary research for a sustainable agriculture and food sector. *Agron. J.* **100:** 771–776.

Francis, C., Lieblein, G., Gliessman, S., Breland, T. A., Creamer, N., Harwood, R., Salomonsson, L., Helenius, J., Rickerl, D., Salvador, R., Wiedenhoeft, M., Simmons, S., Allen, P., Altieri, M., Flora, C. and Poincelot, R. 2003. Agroecology: The ecology of food systems. *J. Sustain. Agric*. **22:** 99–118.

Francis, C. A., and Porter, P. 2010. Ecology in sustainable agriculture practices and systems. *CRC Crit. Rev. Plant Sci.* (this issue)

Freire, P. 1970. *Pedagogy of the Oppressed*. Translated by Myra Bergman Ramos. Seabury Press, New York.

Gliessman, S. R. 1984. An agroecological approach to sustainable agriculture. **In**: *Meeting the Expectations of the Land.* pp. 160–171. Jackson, W., Berry, W., and Colman, B. Eds., Northpoint Press, Berkeley, California.

Gliessman, S. R. 2007. *Agroecology: The Ecology of Sustainable Food Systems*. CRC Press, Taylor and Francis, New York.

Harms, K., King, J., and Francis, C. 2009. Behavioral changes based on a course in agroecology: A mixed methods study. *J. Nat. Res. Life Sci. Educ.* **38:** 183–194.

Hattie, J., and Marsh, H. W. 1996. The relationship between research and teaching: A meta-analysis. *Rev Educ. Res.* **66:** 507–542.

Hattie, J., and Marsh, H. W. 2002. The relation between research productivity and teaching effectiveness. *J. Higher Educ*. **73:** 603–641.

Hendrickson, C. T., Lve, L. B., and Matthews, H. S. 2006. *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*. Resources for the Future Press, Washington, DC.

Ison, R., Maiteny, P., and Carr, S. 1997. Systems methodologies for sustainable natural resources research and development. *Agric. Systems* **55:** 257–272.

Ison, R., Roling, N., and Watson, D. 2007. Challenges to science and society in the sustainable management and use of water: Investigating the role of social learning. *Environ. Sci. Policy* **10:** 499–511.

Jenkins, A., Breen, R., and Lindsay, R. 2003. *Reshaping Teaching in Higher Education: Linking Teaching with Research*. Routledge Ltd., New York.

Jordan, N., Andow, D. A., and Mercer, K. L. 2005. New concepts in agroecology: A service-learning course. *J. Nat. Resources & Life Sci. Educ*. **34:** 83–89.

Jordan, N, Bawden, R., and Bergmann, L. 2008 Sustainability and epistemic competencies: Facing the 'worldview challenge' in sustainable development of agriculture. *J. Natural Res. & Life Sci. Educ.* **37:** 92–99.

Jordan, N., Boody, G., Broussard, W., Glover, J. D., Keeney, D., McCown, B. H., McIsaac, G., Muller, M., Murray, H., Neal, J., Pansing, C., Turner, R. E., Warner, K., and Wyse, D. 2007. Sustainable development of the agricultural bio-economy. *Science* **316:** 1570–1571.

Kallis, G., Videira, N., Antunes, P., Pereira, A. G., Spash, C. L., Coccossis, H., Quintana, S. C., Del Moral, L., Hatzilacou, D., Lobo, G., Mexa, A., Paneque, P., Matcos, B., and Santos, R. 2006. Participatory methods for water resources planning. *Environ. Planning C-Government and Policy* **24:** 215–234.

Kirschenmann, F. 2009. Farming in the middle: An ethical imperative. **In**: *Organic Farming: The Ecological System.* pp. 325–342. Francis, C.A. Ed., Agron. Monograph 54, Amer. Soc. Agron., Madison, Wisconsin.

Kolb, D. 1984. *Experiential Learning: Experience as the Source of Learning and Development*. Prentice-Hall, Inc., Upper Saddle River, New Jersey.

Lieblein, G., Breland, T. A., Østergaard, E., Salomonsson, L., and Francis, C. 2007. Educational perspectives in agroecology: Steps on a dual learning ladder toward responsible action. *NACTA J*. **51:** 37–44.

Lieblein, G., and Francis, C. 2007a. Integration of teaching and research. *Proceedings European Network of Organic Agriculture Teachers (ENOAT).* pp. 28–43. Caporali, F., Lieblein, G., von Fragstein, P., and Francis, C. Eds., Pieve Tesino (TN), Italy, Aug. 29–Sept. 2.

Lieblein, G., and Francis, C. 2007b.. Towards responsible action through agroecological education. *Italian J. Agronomy/Riv. Agron*. **2:** 79–86.

Lieblein, G., Francis, C., Barth-Eide, W., Torjusen, H., Solberg, S., Salomonsson, L., Lund, V., Ekblad, G., Persson, P., Helenius, J., Loiva, M., Sepännen, L., Kahiluoto, H., Porter, J., Olsen, H., Sriskandarajah, N., Mikk, M., and Flora, C. 2000a. Future education in ecological agriculture and food systems: a student-faculty evaluation and planning process. *J. Sustain. Agric*. **16:** 49–69.

Lieblein, G., Francis, C., and King, J. 2000b. Conceptual framework for structuring future agricultural colleges and universities. *J. Agric. Educ. Extension (Wageningen)* **6:** 213–222.

Lieblein, G., Francis, C., Salomonsson, L., and Sriskandarajah, N. 1999. Ecological agriculture research: Increasing competence through PhD courses. *J. Agric. Education and Extension* **6:** 31–46.

Lieblein, G., Moulton, M., Waalen, W., Breland, T. A., Francis, C., Sriskandarajah, N., Porter, J., Helenius, J., Salomonsson, L., and Langer, V. 2005. Systems thinking and experiential learning: a Nordic net-based course in agroecology: Integrating student learning and teacher collaboration. *European Journal of Open and Distance Learning [EURODL]* Vol. 1. [http://eurodl.org/materials/contrib./2005/Lieblein.htm].

Lieblein, G., Østergaard, E., and Francis, C. 2004. Becoming an agroecologist through action education. *Intl. J. Agric. Sustainability* **2:** 1–7.

Liu, J. G., Dietz, T., Carpenter, S. R., Folke, C., Alberti, M., Redman, C. L., Schneider, S. H., Ostrom, E., Pell, A. N., Lubchenco, J., Taylor, W. W., Ouyang, Z. Y., Deadman, P., Kratz, T., and Provencher, W. 2007. Coupled human and natural systems. *Ambio* **36:** 639–649.

Mandarano, L. A. 2008. Evaluating collaborative environmental planning outputs and outcomes: restoring and protecting habitat and the New York New Jersey Harbor Estuary Program. *J. Planning Educ. Res.* **27:** 456–468.

Margerum, R. D. 2002. Evaluating collaborative planning: Implications from an empirical analysis of growth management. *J. Amer. Planning Assoc*. **68:** 179–193.

Mezirow, J. 1996. Contemporary paradigms of learning. *Adult Educ. Quart*. **46:** 158–172.

Mittelstrass, J. 1998. *Die Häuser des Wissens.* Wissenschaftstheoretische Studien. Frankfurt/Main, pp. 29–48.

Olsson, P., Folke, C., Galaz, V., Hahn, T., and Schultz, L. 2007. Enhancing the fit through adaptive co-management: Creating and maintaining bridging functions for matching scales in the Kristianstads Vattenrike Biosphere Reserve, Sweden. *Ecol. Soc*. **12:** Art. No. 28.

Pahl-Wostl, C., and Hare, M. 2004. Process of social learning in integrated resources management. *J. Commun. Appl. Psychol*. **14:** 193–206.

Palmer, S., Nilsson, A., and Roigart, A. 2008. *Dynamic change in rice production systems in the Mekong Delta: a students field study report from An Gian*. Rapporter Institutionen för Stad och Land, number 3/2008. Swedish Univ. Agric. Sci., Uppsala, Sweden.

Peters C., Bills N., Lembo A., Wilkins, J., and Fick, G. 2009. Mapping potential foodsheds in New York State: A spatial model for evaluating the capacity to localize food production. *Renew. Agric. Food Syst*. **24:** 72–84.

Pickett S., Cadenasso, M., and Grove, J. 2005. Biocomplexity in coupled natural-human systems: A multidimensional framework. *Ecosystems* **8:** 225–232.

Pogranichniy, S., Burras, L., Polito, T. A., and Wiedenhoeft, M. H. 2001. Freshman learning communities in agriculture: Observations and assessment. *J. Nat. Res. Life Sci. Educ.* **30:** 104–110.

Pretty, J. 1995. Participatory learning for sustainable agriculture. *World Devel.* **23**(8): 1247–1263.

Rickerl, D., and Francis, C. (Eds.). 2004. *Agroecosystems analysis.* Monograph Series No. 43, Amer. Soc. Agron., Madison, Wisconsin.

Robertson, G. P., Allen, V. G., Boody, G., Boose, E. R., Creamer, N. G., Drinkwater, L. E., Gosz, J. R., Lynch, L., Havlin, J. L., Jackson, L. E., Pickett, S. T. A., Pitelka, L., Randall, A., Reed, A. S., Seastedt, T. R., Waide, R. B., and Wall, D. H. 2008. Long-term agricultural research: A research, education, and extension imperative. *Bioscience* **58:** 640–645.

Salner, M. 1986. Adult cognitive and epistemological development in systems education. *Syst. Res.* **3:** 225 232.

Salomonsson, L., Francis, C., Lieblein, G., and Furugren, B. 2005. Just in time education. *NACTA J*. December **49:** 5–13.

Salomonsson, L., Nilsson, A., Palmer, S., Roigart, A., and Francis, C. 2008. Farming systems education: Case study of Swedish test pilots. *Renewable Agric. Food Systems* **24:** 48–59.

Samson, F., and Knopf, F. 1994. Prairie conservation in North America. *Bioscience* **44:** 418–421.

Schunn, C. D., Crowley, K., and Okada, T. 1998. The growth of multidisciplinarity in the cognitive science society. *Cognitive Sci.* **22:** 107–130.

Sriskandarajah, N., Bawden, R. J., and Packham, R. G. 1990. Systems agriculture: A paradigm for sustainability. *AFSRE Newsletter* **2:** 1–5.

Steyaert, P., Barzman M., Billaud J. P., Brives, H., Hubert, B., Ollivier, G., and Roche, B. 2007. The role of knowledge and research in facilitating social learning among stakeholders in natural resources management in the French Atlantic coastal wetlands. *Environ. Sci. Policy* **10:** 537–550.

Tonn, B., English, M., and Travis, C. 2000. A framework for understanding and improving environmental decision making. *J. Environ. Planning Management* **43:** 163–183.

Uphoff, N. (Ed.). 2002. *Agroecological Innovations: Increasing Food Production with Participatory Development*. Earthscan Publ., Sterling, Virginia.

Warner, K. D. 2008. *Agroecology in Action Extending Alternative Agriculture Through Social Networks.* MIT Press, Cambridge, Massachusetts.

Wezel, A., Bellon, S. Dore, T., Francis, C., Vallod, D., and David, C. 2009 Agroecology as a science, a movement or a practice. *Agron. Sustain. Devel*. (DOI: 10.1051/agro/200904). Available online at: www.agronomy-journal.org Accessed 21 September 2009.

Wiedenhoeft, M., and Loynachan, T. 2009. Student-centered learning experiences at Iowa State University. *Agron. Abstr*., 2009.54968, Amer. Soc. Agron., Madison, Wisconsin. http://acs.confex.com/crops/2009am /webprogram/Paper54968.html, Accessed 24 January 2010.

Wiedenhoeft, M., Simmons, S., Salvador, R., McAndrews, G., Francis, C., King, J., and Hole, D. 2003. Agroecosystems analysis from the grass roots: A multidimensional experiential learning course. *J. Natural Res. Life Sci. Educ*. **32:** 73–79.

Wilson, K., and Morren Jr., G. E. B. 1990. *Systems Approaches for Improvement in Agriculture and Resource Management*. Macmillan Publ., New York.