Research Networking to Evaluate the Sustainability of Horticultural Production Systems

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Abstract

Although it is widely recognized by researchers who study agricultural production systems that evaluating the sustainability of these systems is vital, few studies of this nature have been published. One difficulty may be in defining what constitutes sustainability and how it should be measured, while another may be in networking with the necessary multi-disciplinary research team to carry out this type of study. Nevertheless, the study of agricultural production systems is important to the sustainability of farms, rural communities, and society because these studies compare actual farming systems, revealing their strengths and weaknesses. Using the recent study on the sustainability of organic, integrated, and conventional apple production systems in Washington State, USA, as an example, we will address the following critical questions about evaluating sustainability and how research networking fits into this scientific approach: What constitutes a whole system's approach to studying sustainability in horticultural production systems? What are the characteristics of a successful study of horticultural production systems? Why aren't more studies of horticultural production systems performed or reported in the literature? What are the future directions of research on horticultural production systems?

INTRODUCTION

Although it is now widely recognized by researchers who study agricultural production systems that it is vital to evaluate the sustainability of these systems, few studies of this nature have been published. In order to evaluate the sustainability of agricultural production systems, however, it is first necessary to realistically represent the selected production systems, whether they be organic, integrated, conventional, biodynamic, or some other type, as farmers would experience them. Second, it is necessary to determine which indicators of sustainability are to be measured; but this first requires a clear definition of sustainability. Finally, it is necessary to network with the essential personnel that represent the scientific disciplines required to carry out the study. Using our experience in conducting a study comparing organic, conventional, and integrated apple production systems in Washington State, USA, we will explain how research networking can be used to successfully evaluate the sustainability of horticultural production systems.

AGRICULTURAL SUSTAINABILITY AND SYSTEM'S RESEARCH

Agricultural sustainability is defined by the U.S. Dept. Agr. in terms of economic viability, ecological health, and social equity (USDA-CREES, 2002). Reganold et al. (1990) stated that for a farm to be sustainable in the long term, it must produce adequate yields of high quality, be profitable, protect the environment, conserve resources (i.e., soil, water, genetic, and energy resources), and be socially responsible. A different approach to defining agricultural sustainability was recently presented by Tilman et al. (2002). They defined "sustainable agriculture as practices that meet current and future societal needs for food and fiber, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered." A key element of this definition is the inclusion of "ecosystem services", for example, the value attributable to improved soil quality for reducing soil erosion, preventing groundwater pollution, and providing water and nutrients more efficiently to the crop. This broader definition of agricultural sustainability requires a fuller accounting of all the benefits and costs of both conventional and alternative agricultural production systems, which then becomes the basis for future agricultural policy and practice (Tilman et al., 2002).

There can be confusion over what constitutes a whole system's approach to studying the sustainability of horticultural production systems. Obviously, the study must compare different production systems, such as, conventional, organic, or integrated. The precise practices and equipment used in these production systems, however, will vary by country (because of different certification standards), by regions (because of different biotic and climatic limitations), and even by farm (because of farmers' different management skills and styles). These studies also must continue over a sufficient period of time to fully reflect changes in soil properties, evolution of management practices, effects of market forces, and, especially for perennial crops, the period of time from planting until full production. These changes in the characteristics of horticultural production systems over time dictate a minimum of about six years of continued evaluation. Even annual cropping systems, which typically require rotation with other crops, necessitate an extended period of study to fully reflect changes in these factors over multiple rotations. Ideally, studies of horticultural production systems should be replicated over multiple sites. However, even when multiple sites are used it is difficult to attribute differences in performance among systems at different sites to specific site characteristics. This is because site differences may be due to a multitude of factors, including soil characteristics, water quality, climate, management skills of the farmers and/or researchers, level of training by labor, access to capital, market forces, crop varieties, and in the case of perennial crops, rootstock selection. Studies of horticultural production systems are usually sufficiently costly to negate the feasibility of funding agencies supporting research at multiple sites, unless only a small subset of sustainability indicators are evaluated.

There is also much debate over whether studies of horticultural production systems are more or less valid if performed on a commercial farm or at a public research institution. Studies performed at research institutions may involve farmers and/or extension personnel in a consultative role, but this arrangement does not accurately reflect how farmers actually make decisions on their farms, where risk assessment and aversion are market driven and decision-making is principally non-participatory, despite the fact that most farmers receive advice from commercial pest-control advisors and horticultural consultants. Nevertheless, there are risks associated with on-farm studies, because the research investigators usually do not have as much control over day-to-day operations and their inherent demand for scientific precision may not be sufficiently adhered to by the participating farmer. In addition, proper replication of the systems at an experimental site on a farm may be compromised because the farmer: 1) may not be sufficiently aware of their importance, 2) may overlook them in the day-to-day operations, or 3) may decide not to support the research for the many years needed to collect adequate data to evaluate the systems. Nevertheless, replication is essential for proper statistical analysis, even on a commercial farm, and without it publication in scientific journals may be compromised.

Agricultural sustainability is an inherently complex concept (Barrett and Odum, 2000) and not readily quantifiable. Agricultural production systems are also complex, and therefore, evaluation of their sustainability requires consideration of multiple components. This necessitates multi- and inter-disciplinary research approaches, the success of which depends upon the availability and willingness of scientists from different disciplines to participate in the study and interact with one another. Sometimes, the principal investigator(s) can evaluate and analyze several aspects of the study themselves, especially if they have skilled technicians or talented graduate students. Unquestionably, at this point in the evolution of research on agricultural production systems, all studies should emphasize agroecosystem processes that integrate the physical, chemical, biological, and environmental properties right from the level of the soil-plant-atmosphere continuum up to the scale of an entire planting, farm, community, or bioregion. Besides being descriptive, studies of horticultural production systems also should be integrative, with analyses and interpretations of the interactions among the multiple factors being studied. Quantitative integration of these multiple factors requires multivariate statistical and modeling approaches, such as, indices (e.g., Glover et al., 2000) or life-cycle assessments (ISO, 1997; Hass et al., 2001; Schenck, 2001). Finally, studies of horticultural production systems should be diagnostic so that causes and effects can be separated and identified and farm system policies can be extrapolated to other farms and crops.

BRIEF HISTORY OF AGRICULTURAL PRODUCTION SYSTEMS RESEARCH

A history of research on agricultural production systems must certainly begin with the classic studies on the Rothamsted experimental farm at the Institute of Arable Crops Research in the United Kingdom. These studies, started in 1843 by John Lawes and Henry Gilbert, have examined the effects of inorganic and organic manures and weed control methods on yields, soil properties, and weeds of winter wheat (*Triticum aestivum* L.), with and without rotations, continuously for more than 150 years (IARC-Rothamsted, 2002).

A major component of research on farming systems has involved international rural development by the developed countries for the small, resource-poor farmers in developing countries, which was begun in the 1960s. This research is coordinated by the Consultative Group on International Agricultural Research (CGIAR) and has involved many of the International Agricultural Research Institutes [e.g., CIMMYT for maize (*Zea mays* L.) and wheat (*T. aestivum* L.), IRRI for rice (*Oryza sativa* L.), and CATIE for tropical crops]. Most of this research has been conducted in Africa, Latin America, and Asia and has been financed by the World Bank and the Food and Agriculture Organization of the United Nations. A review of international development research on farming systems has recently been compiled into a volume edited by Collinson (2000). Despite controversies over issues of what technologies are appropriate for adoption by subsistence farmers in developing countries and whether domestic or “cash” crops for export should be produced, many positive benefits have come from this research, including improvements in soil quality, enhancement of human nutrition through alternative horticultural crop production, and empowerment of women.

Recently, the results of several long-term studies of agricultural production systems with an agroecosystem emphasis have been reported. One of these studies is the Swiss “DOK” systems trial (Mäder et al., 2002), begun in 1978. In this study, yields of a wheat-potato-clover (*T. aestivum* L.-*Solanum tuberosum* L.-*Trifolium* spp.) rotation were lower from two organic systems (i.e., Demeter-certified and bioorganic) than from two conventional systems (i.e., fertilized either with both inorganic and organic fertilizers or with only inorganic fertilizers). However, both organic systems utilized fertilizer and energy inputs more efficiently than did the conventional systems. The authors concluded that because the organic systems had enhanced soil fertility and higher biodiversity, they would be less dependent upon external inputs than would the conventional systems.

Another study began in 1981 at the Rodale Research Center in Pennsylvania, USA, examined transition from a conventional system using fertilizers and pesticides to two low-input systems in a maize-soybean [*Z. mays* L.-*Glycine max* (L.) Merr.] rotation. In the low-input systems, which also included forage/silage crops, nutrients were either supplied by manure or plowed-under legumes. In the first four years of this study, weed competition and insufficient nitrogen limited corn (*Z. mays* L.) yields in the low-input systems, but soybean [*G. max* (L.) Merr.] yields were higher in these systems than in the conventional system (Liebhardt et al., 1989). However, average cumulative yields (Drinkwater et al., 1998) and economic profitability (Hanson et al., 1996) during the sixth and fifteenth years of the study were comparable for the low-input and conventional systems. Nevertheless, the low carbon-to-nitrogen residues used in the low-input systems to maintain soil fertility, together with these systems more diverse crop rotation cycles, significantly increased the retention of carbon and nitrogen in the soil (Drinkwater et al., 1998). These characteristics of the low-input systems have important implications for environmental quality through increased carbon sequestration by the soil, reduced CO_2 emissions from their lower energy use, and increased availability of biologically active nitrogen through leguminous nitrogen fixation.

Two separate but related seven-year studies on the sustainability of alternative, conventional, and reduced-tillage farming systems for row crops and small grains were established in South Dakota, USA in 1985. The alternative system included a green manure crop in the rotation and additions of animal manure, but no commercial fertilizers or pesticides. The alternative system had the highest yields and profitability in row crop production, whereas small grain yields were lowest in the alternative system but its economic performance was similar to the conventional system (Smolik et al., 1995). For both row crops and small grains, the alternative system had the lowest year-to-year variation in productivity and was the most energy efficient. Also, the alternative systems depended less on government payments for their profitability, and therefore, the authors concluded that the trend toward increasing farm size would be slowed if alternative systems were more widely adopted.

A long-term study that includes horticultural crops is the Sustainable Agricultural Farming Systems (SAFS) project conducted at the Univ. of California (UC) at Davis in the Sacramento Valley. This replicated study, begun in 1989, includes a four-year tomato-safflower-corn-wheat (*Lycopersicon esculentum* Mill.-*Carthamus tinctorius* L.-*Z. mays* L.- *T. aestivum* L.) rotation, followed by double-cropped beans (*Phaseolus vulgaris* L.) in the conventional system and oat-purple vetch (*A. sativa* L.-*V. benghalensis* L.) in the organic and low-input systems. Unique to this study compared with others, all combinations of rotation sequences are included as replicates in order to account for variation due to years. While both the organic and low-input systems include an annual winter vetch (*V. villosa* Roth) cover crop, the organic system uses composted animal manure and fertilizers and pesticides approved by an organic certifying agency (i.e., California Certified Organic Farmers). The low-input system omits the compost and uses reduced rates of synthetic fertilizers and pesticides, whereas the conventional system uses labeled rates of synthetic fertilizers and pesticides. This interdisciplinary study was initiated by scientists, farm advisors, and farmers, and so includes a multi-disciplinary team focusing on soil microbiology, economics, pest management, agronomy, and cover crop management (Temple et al., 1994). This study is also unique in that it integrates the advice of leading conventional and organic growers so as to provide the best crop management practices and economic interpretations for each production system. It was found that in most years the nitrogen-demanding tomato (*L. esculentum* L.) and corn (*Z. mays* L.) crops had lower yields in the organic and low-input systems than in the conventional system, due to less available nitrogen and greater weed competition in these systems compared with the conventional system (Clark et al., 1999). Price premiums in the organic system, which may not be viable long-term, made it the most profitable system, however. Nevertheless, the organic and low-input systems, with their added carbon sources, had more stored nitrogen in the top soil and lower nitrogen losses than the conventional system (Poudel et al., 2001), and they also had better water infiltration during irrigations and lower evapotranspiration (Colla et al., 2000).

Studies of horticultural production systems of perennial crops are more limited. In California, a short-term, three-year replicated study was initiated in 1989 in a mature, commercial ‘Granny Smith’ apple (*Malus* × *domestica* Borkh.) orchard in which a conventional system was compared with an organic system during conversion of it from conventional management. The organically managed system produced greater yields than the conventional system in two out of the three years, but fruit from the organic system were smaller because of insufficient fruit thinning by hand (Swezey et al., 1994). This also resulted in a general trend toward alternate bearing in the organic system. Using mulched and unmulched organic subplots, the authors found that the significantly greater weed growth in the organic system compared with the conventional system had no effect on yields in these mature apple trees. The organic system had higher material and labor inputs in all years, but greater net financial returns in 1990 and 1991 because of the 33-38% premiums received for certified organic fruit in those years (Swezey et al., 1994, 1998). (Presently, a three-year transitional period, in which only organic practices are used, is required for organic certification by the U.S. Dept. Agr. National Organic Program.) There were no differences between the systems in codling moth (*Cydia pomonella* L.) damage because of successful control in the organic system by codling moth granulosis virus and pheromone mating disruption, and differences in damage by secondary pests varied between the systems (Swezey et al., 1994). By the end of the second year of organic management, microbial biomass carbon in the topsoil was usually greater in the organic plots; however, respiratory carbon loss via CO_2 was negligible in both production systems (Werner, 1997). Potentially mineralizable nitrogen in the topsoil also became greater in the organic system by the third year of organic management. Colonization of apple roots by vesicular-arbuscular mycorrhizae was greater in the organic system during the second and third years of organic management, which may account for the increased phosphorus measured in bark and leaf tissues of these trees (Swezey et al., 1994). In the winter and spring of the fourth year of organic management, the organic plots had more earthworms than the conventional plots (Werner, 1997).

Another study of biological (i.e., organic), integrated, and conventional apple (*M.* × *domestica* Borkh.) production systems focused only on pests, pest damage, and predator-parasite interactions (Suckling et al., 1999). This on-farm study was replicated in three production regions of New Zealand (Hawkes Bay, Canterbury, and Otago), but there was no replication of the systems on each individual farm. This study also has been relatively short-term, initiated in 1995 and evaluated during the 1995-1996 growing season. The authors concluded that the integrated system was more sustainable for the New Zealand apple industry because it didn’t have the potential insecticide resistance problems of the conventional system, and unlike the biological system it was capable of controlling key quarantine pests of New Zealand’s export markets.

The preliminary results of a study of integrated and organic apple production systems, planted in 1995 at the Swiss Federal Research Station for Fruit-Growing in Wädenswil, are reported in this volume (Bertschinger et al., 2004). Fruit yields were slightly lower for the four cultivars in the trial produced by organic methods than when produced by integrated methods. These yield differences were attributed to lower leaf chlorophyll and higher mice and weed competition in the organic plots. In general, the internal fruit quality attributes (i.e., firmness and soluble solids content) were more favorable in organic fruit, while the external fruit quality attributes (i.e., fruit size and color), upon which basis farmers are paid, were higher for integrated fruit. Despite production costs being higher in the organic system, the price premiums for organic fruit made this system the most profitable overall.

These studies indicate that while yields, or marketable fruit size, may be less in alternative production systems, soil nutrient utilization and energy efficiency are often better than in conventional systems because of the greater biological diversity in the alternative systems. Therefore, alternative farming systems appear to be less dependent on external inputs for their sustainability than are conventional systems.

RESEARCH NETWORKING FOR STUDYING HORTICULTURAL PRODUCTION SYSTEMS

In order for a study of horticultural production systems to be successful, a supportive system of research networking and information sharing among the study participants is essential. Using our study of three apple production systems, we will address the critical aspects of how research networking fits into a scientific approach of evaluating the sustainability of different horticultural production systems.

We planted ‘Golden Delicious’ apple (*M.* × *domestica* Borkh.) trees on M.9

rootstock in a high-density training system at a commercial orchard in the Yakima Valley of Washington State, USA, in May 1994. Three production systems, replicated in four blocks, were represented in the study: organic, conventional, and integrated. The organic system adhered to Washington State organic certification standards, with fruit thinning by hand. Chemical blossom and fruit thinners were used in the conventional and integrated systems. Pest management was identical in both conventional and integrated systems, and pheremone mating disruption was used to control codling moth (*Cydia pomonella* L.) in all three systems. Chemical weed control was used in the conventional and integrated systems, although fewer applications were applied in the integrated system. The organic system used a variety of weed control methods over the years, including organic and synthetic mulches, cultivation, and mowing. Nutrients were supplied to the tree rows of the organic system as composted poultry manure in the first two years. The conventional system received synthetic nitrogen fertilizers in the first two years and the integrated system received half its nitrogen as synthetic fertilizer and half as composted manure in the first two years. Foliar nutrients were applied to all three systems in each year. These and other management practices were chosen cooperatively by the farmers, professional consultants, and research leaders.

We measured several indicators of agricultural sustainability in these three production systems from 1994-1999. All three systems produced similar fruit yields, but the organic system tended to have smaller fruit (Reganold et al., 2001a). When compared with the conventional and integrated systems, the organic system produced sweeter and less tart apples, had higher profitability during the years of the study, and was more energy efficient. The organic and integrated systems had higher soil quality than the conventional system, based on a soil quality index that we developed (Glover et al., 2000). Both alternative systems also had lower negative environmental impact from pesticide use than the conventional system (Reganold et al., 2001a). Based on our data, we concluded that the organic system ranked first in environmental and economic sustainability, the integrated system second, and the conventional system last. We also concluded that while better soil and environmental quality of alternative production systems are valuable, their value has been largely overlooked in the marketplace and yet they still come at a financial cost to growers. Therefore, without economic incentives that value these benefits, such as, price premiums or environmental subsidies (as in many European countries), growers using more sustainable production methods may be unable to maintain profitable enterprises.

The range of sustainability indicators that we studied required that we measure many parameters, including yields, soil properties, horticultural performance, fruit quality and storability, consumer preferences, production costs and returns, pest interactions, and pesticide and energy use. In order to conduce this study and measure this broad range of sustainability indicators, we assembled a team that included the farmer, orchard manager, horticultural and pest management consultants, and scientists in the fields of soils, horticulture, post-harvest, food science, soil pathology, soil ecology, agricultural economics, and statistics.

It may be asked, however, why are studies of horticultural production systems important? First, they are important because they compare actual farming systems, and these comparisons can determine if the claims for or against a particular farming system are true or false. Second, studies of farming systems can uncover their strengths and weaknesses, the knowledge of which can be incorporated into commercial farming practices or can indicate where future research should be focused. This knowledge also may contribute to reducing the negative environmental impacts of current agricultural practices. Third, studies of farming systems tend to bridge across academic, extension, consultant, and farming viewpoints, which can broaden the perspective of all participants in the food production chain. And finally, studies of farming systems can help farmers to be more competitive and rural communities to be more viable, both of which are beneficial to society.

What are the characteristics of a successful study of horticultural production systems? First, there must be committed participants from multiple disciplines. Elizabeth Bird (2000), in her case studies of research on food systems, found that the reasons why people participated in this type of research were that: 1) it was intrinsically meaningful and interesting, 2) it provided partnerships and teamwork that were rewarding and enjoyable, 3) it was recognized and appreciated if effectively performed, 4) it attracted new or continued funding, and 5) it provided specialized training for graduate students. Second, a successful study usually attracts scientists from other disciplines who were not initially involved in the study, since the study site becomes an “open” laboratory. Third, the site must be available long term, so that the sustainability of different production systems can be satisfactorily evaluated over many years. The commercial orchard we are using for our study has been available now for ten years. Fourth, consistent funding is essential for a successful study. Sometimes, seed money is available to initiate the study, as in our project with funding from the Organic Farming Research Foundation and the Washington State Tree Fruit Commission. In addition, substantial funding came to us from three, three-year grants from the Agricultural Systems and Managed Ecosystems programs of the U.S. Dept. Agr. National Research Initiative Competitive Grants Program (USDA-NRICGP). The UC-SAFS project has received institutional support from the UC Sustainable Agriculture and Education Program (SAREP), which has contributed to its success. Fifth, a successful study of horticultural production systems needs a management-decision framework that is participatory, yet at the same time represents the type of decision-making usually made in commercial farming, which is not typically by consensus. The management skill of the researchers and farmers is also a factor. In our study, neither we nor the farmer had prior experience in commercial organic farming, yet the farmer was a highly skilled conventional farmer. Sixth, agricultural production systems evolve as new scientific knowledge becomes available and new technologies are developed. Today, conventional agriculture is becoming more integrated and even some organic practices are being adopted by conventional farmers, and vice versa. This evolution in farming practices may simply reflect differences between crops and producing regions, which can make identifying contributing factors within systems difficult. Finally, the results of a successful study of horticultural production systems should be published for a variety of audiences. In our study, besides our publications of overall sustainability in *Nature* (Reganold et al., 2001a) and soil quality in *Agriculture, Ecosystems and Environment* (Glover et al., 2000), we have also published our results in the proceedings from international meetings (Reganold et al., 2000; Andrews et al., 2001a, 2001b), as enterprise budgets (Glover et al., 2001), and in industry journals (Reganold et al., 2001b; Andrews et al., 2002).

Why aren’t more studies of horticultural production systems performed or reported in the literature? Studies of horticultural production systems may not be undertaken because key participants are unwilling or unavailable, or because there is no satisfactory study site. The potential sponsoring institution (e.g., university or research institute) may be unsupportive of this type of research. One reason for this may be that the institution has other priorities (e.g., biotechnology) or it may be simply because of the delayed publication of results from research on horticultural production systems owing to the long-term nature of these studies. Another reason may be because most researchers have little prior training or experience in interdisciplinary research on horticultural production systems. Finally, more studies of horticultural production systems may not occur because of unavailable funding, especially with the high start-up costs for perennial horticultural crops. The lack of grant funding to support studies on the sustainability of horticultural production systems may be also due to biases by grant reviewers. In our experience, criticisms by grant reviewers have included: 1) long-term studies are repetitious, 2) too long from planting until first harvest (e.g., 3-4 years or more for a perennial horticultural crop), 3) insufficient replication and/or small plot size, 4) only a single site to be studied, 5) not hypothesis-based research, 6) difficulty in defining or analyzing sustainability, and 7) unjustified biases against a particular production system (especially organic-type systems). Some of these criticisms can be acceptably addressed in grant proposals, while others may be more difficult to explain to the reviewers' satisfaction.

We believe that the future of research on horticultural production systems will more and more have an international focus, especially in regards to marketing because of the global economy. We also believe that refinements will be made in analytical approaches to evaluating sustainability, such as, life-cycle assessments and comparative indexes. The current emphasis on ecosystem processes and services and their valuation will continue, as well as a focus on the human health effects of horticultural production systems. One outcome of the expansion of research on horticultural production systems that should not be overlooked is the availability of more trained personnel with expertise and experience to conduct this type of research.

CONCLUSIONS

The study of horticultural production systems is important to the sustainability of farms, rural communities, and society because these studies compare actual farming systems, revealing their strengths and weaknesses. These studies are complicated by the fact that both sustainability and farming systems are inherently complex and difficult to quantify. A long-term commitment by the participants, supporting institutions, and funding agencies is required for a successful study of horticultural production systems. Nevertheless, these studies can be rewarding because they bring together the perspectives of farmers, professional consultants, extension personnel, and scientists. They also provide a training ground for graduate students who will be the research leaders of the future for studying farming systems. With the increasing recognition of the importance of horticultural crops to the global economy, ecosystem services, and human health, even more rewards can be gained from the study of the sustainability of horticultural production systems.

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Literature Cited

Andrews, P.K., Glover, J.D. and Reganold, J.P. 2001a. Horticultural performance, soil quality, and orchard profitability of integrated, organic, and conventional apple production systems. In: J. Avilla and F. Polesny (eds.). Proc. 5th Intl. Conf. on Integrated Fruit Production. IOBC/WPRS Bulletin 24(5): 393-400.

Andrews, P.K., Fellman, J.K., Glover, J.D. and Reganold, J.P. 2001b. Soil and plant mineral nutrition and fruit quality under organic, conventional, and integrated apple production systems in Washington State, USA. Proc. 4th Intl. Symp. on Mineral Nutrition of Deciduous Fruit Crops. Acta Hort. 564: 291-298.

Andrews, P.K., Reganold, J.P., Hinman, H.R. and Glover, J.D. 2002. Horticultural performance, soil quality, and orchard profitability of integrated, organic, and conventional apple production systems. Good Fruit Grower 53(9): 28 (May 1).

Barrett, G.W. and Odum, E.P. 2000. The twenty-first century: The world at carrying capacity. BioScience 50: 363-368.

Bertschinger, L., Mouron, P., Dolega, E., Höhn, H., Holliger, E., Husistein, A., Schmid, A., Siegfried, W., Widmer, A., Zürcher, M. and Weibel, F. 2003. Ecological apple production: a comparison of organic and integrated apple-growing. Proceedings of the 1st Symposium on Sustainability in Horticulture, International Horticultural Congress, August 12-16, 2002, Toronto, Canada. Acta Hort. 638: 321-332.

Bird, E. 2000. Integrative analysis of systems research case studies. Center for Integrated Agricultural Systems (http://www.wisc.edu/cias/index.html), Univ. Wisconsin, Madison.

Clark, S., Klonsky, K., Livingston, P. and Temple, S. 1999. Crop-yield and economic comparisons of organic, low-input, and conventional farming systems in California's Sacramento Valley. Amer. J. Alt. Agric. 14: 109-121.

Colla, G., Mitchell, J.P., Joyce, B.A., Huyck, L.M., Wallender, W.W., Temple, S.R., Hsiao, T.C. and Poudel, D.D. 2000. Soil physical properties and tomato yield and quality in alternative cropping systems. Agron. J. 92: 924-932.

Collinson, M. (ed.) 2000. A History of Farming Systems Research. Food and Agriculture Organization of the United Nations (Rome, Italy) and CABI International (Wallingford, United Kingdom).

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

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. Ecosystem Env. 80: 29-45.

Glover, J., Hinman, H., Reganold, J. and Andrews, P. 2001. A cost of production analysis of conventional vs. integrated vs. organic apple production systems. Research Bulletin, Wash. State University Cooperative Extension, Pullman. XB10401 (http://farm.mngt.wsu.edu/PDFDocuments/xb1041.pdf).

Hanson, J.C., Lichtenberg E. and Peters, S.E. 1996. Organic versus conventional grain production in the mid-Atlantic: an economic and farming system overview. Amer. J. Alt. Agric. 12: 2-9.

Haas, G., Wetterich, F. and Kopke, U. 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agriculture, Ecosystems and Environment 83: 43-53.

Institute of Arable Crops Research (IARC)-Rothamsted. 2002. Rothamsted's classic experiments. http://www.iarc.bbsrc.ac.uk/res/corporate/ltexperiments/ltexpintro.htm (Accesses Aug. 2002).

ISO. 1997. Environmental management - Life cycle assessment - Principles and framework. ISO 14040. The International Organization for Standardization, Geneva, Switzerland.

Liebhardt, W.C., Andrews, R.W., Culik, M.N., Harwood, R.R., Janke, R.R., Radke, J.K. and Rieger-Schwartz, S.L. 1989. Crop production during conversion from conventional to low-input methods. Agron. J. 81: 150-159.

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

Poudel, D.D., Horwath, W.R., Mitchell, J.P. and Temple, S.R. 2001. Impacts of cropping systems on soil nitrogen storage and loss. Agric. Systems 68: 253-268.

Reganold, J.P., Papendick, R.I. and Parr, J.F. 1990. Sustainable agriculture. Scientific Amer. 262: 112-120.

Reganold, J.P., Glover, J.D. and Andrews, P.K. 2000. Soil quality, crop yield, and orchard profitability of organic, conventional, and integrated production systems, pp. 250-253. In: T. Alfoldi, W. Lockeretz and U. Niggli (eds.) The world grows organic. Proc. 13th IFOAM Conference. International Federation of Organic Agriculture Movements, Postfach, Switzerland.

Reganold, J.P., Glover, J.D., Andrews, P.K. and Hinman, H.R. 2001a. Sustainability of three apple production systems. Nature 410: 926-930.

Reganold, J.P., Glover, J.D., Andrews, P.K. and Hinman, H.R. 2001b. Melicoltura convenzionale, integrata o biologica? Una scelta difficile. Fruitticoltura 63: 33-36.

Schenck, R. 2001. Farm environmental management systems in Nebraska: A case study. Institute for Environmental Research and Education. http://www.iere.org/documents/ Ecospheres.pdf (Accessed Aug. 2002).

Smolik, J.D., Dobbs, T.L. and Rickerl, D.H. 1995. The relative sustainability of alternative, conventional, and reduced-till farming systems. Amer. J. Alt. Agric. 10: 25-35.

Suckling, D.M., Walker, J.T.S. and Wearing, C.H. 1999. Ecological impact of three pest management systems in New Zealand apple orchards. Agric. Ecosystems Env. 73: 129-140.

Swezey, S.L., Rider, J., Werner, M.R., Buchanan, M., Allison, J. and Gliessman, S.R. 1994. Granny Smith conversions to organic show early success. Calif. Agric. 48(6): 36-44 (Nov.-Dec.).

Swezey, S.L., Werner, M.R., Buchanan, M. and Allison, J. 1998. Comparison of conventional and organic apple production systems during three years of conversion to organic management in coastal California. Amer. J. Alt. Agric. 13: 162-180.

Temple, S.R., Friedman, D.B., Somasco, O., Ferris, H., Scow, K. and Klonsky, K. 1994. An interdisciplinary, experiment station-based participatory comparison of alternative crop management systems for California's Sacramento Valley. Amer. J. Alt. Agric. 9: 64-71.

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

U.S. Dept. Agr.-Cooperative State Research, Education, and Extension Service (USDA-CREES). 2002. Economic and Community Systems Sustainable Agriculture. http://www.reeusda.gov/ecs/sustag.htm (Accessed Aug. 2002).

Werner, M.R. 1997. Soil quality characteristics during conversion to organic orchard management. Appl. Soil Ecol. 5: 151-167.