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Ecology in Sustainable Agriculture Practices and Systems

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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.

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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 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

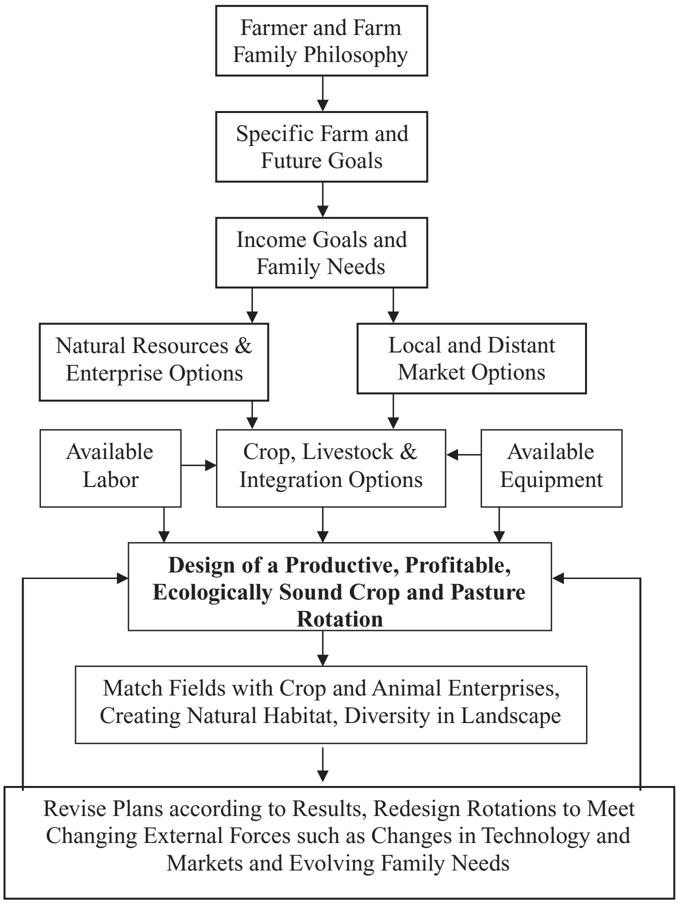

FIG. 1. Flow chart of planning decisions for sustainable field and farm rotations (inspired by Johnson and Toensmeier, 2009).

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

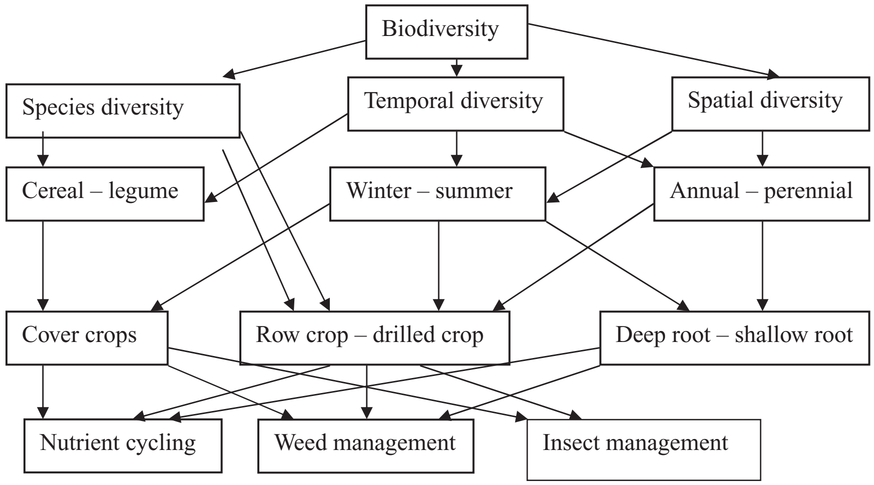

FIG. 2. Ecological principle of biodiversity expressed in practices for design of sustainable crop rotations and systems, illustrating major interactions and consequences.

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.

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