LINKING ECOLOGICAL SUSTAINABILITY AND WORLD FOOD NEEDS

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Abstract. Ecological approaches to agriculture can provide useful guidelines for addressing world food needs, while avoiding adverse environmental and social impacts. Experiments in both natural and agricultural ecosystems suggest that systems with high plant diversity may be more productive, more stable and more resilient than species-poor systems. In addition, systems with high plant diversity support higher levels of biodiversity in other functional groups, which may enhance the productivity of the plant component. Given these benefits of diverse systems, various approaches for converting conventional high input agricultural systems to more sustainable systems are addressed. Andow and Hidaka's (1989) concept of production syndromes is considered in the context of conversion to sustainable agriculture.

Key words: agroecological design, biodiversity and agriculture, ecological sustainability, input substitution.

1. Introduction

An often repeated concern about agroecological approaches to agricultural production is that these approaches can never achieve yields sufficiently high to ensure food security for growing world populations. Clearly, food production itself is only a small component of food security, and high yields alone will never ensure food security. But productivity does matter to farm households, and in some places at certain times, agricultural productivity may be a vital component of food security. Despite increases in food production, the environmental and social costs of the Green Revolution approach are well documented and widely acknowledged (Conway, 1997; Pingali et al., 1997). Yet the negative consequences of Green Revolution technologies and systems are often described as necessary costs of raising productivity. Thus, it is useful to ask whether ecological approaches can provide any clear guidelines for addressing world food needs, while avoiding adverse environmental and social impacts.

1.1. COMPONENTS OF ECOLOGICAL SUSTAINABILITY

Proponents of agroecological approaches and sustainable agriculture emphasize the importance of ecological sustainability, but the components of sustainability or stability are seldom explored in any detail. In agroecosystems, stability can be evaluated as the constancy of production in the face of environmental perturbations (Conway, 1985). Typically when we talk about sustainability, we mean to convey two related concepts that have been addressed by ecologists for decades in the context of community stability: resilience and resistance.

Environment, Development and Sustainability **1:** 185–196, 1999.

Resistance describes the likelihood of system response to a perturbation. Systems with greater resistance will be less impacted by a perturbation. In the context of agriculture, we are interested in the ability of systems to withstand natural perturbations such as climate fluctuations or pest outbreaks without exhibiting wild fluctuations in yield. Resilience describes the rate of return to original conditions after a perturbation. Systems with greater resilience return rapidly and reliably to original conditions. In agroecosystems, we are looking for resilient systems that can compensate rapidly for droughts or disease epidemics. But note that there is no necessary link between resistance and resilience – systems with high resistance may or may not exhibit high resilience.

1.2. DIVERSITY AND STABILITY REVISITED

What are the characteristics of resistant and resilient systems? Diversity, synergy, and synchrony are some of the characteristics that are consistently identified by proponents of sustainable agriculture. The idea that diversity should impart stability to ecological systems, including agricultural systems, has a long history (e.g., Elton, 1958; Macarthur, 1955). Implicit in many discussions of the effects of diversity is the idea that diversity results in synergy and synchrony. Synergy implies that the outcome of interactions among system components is more than the sum of its parts. In this context, synchrony implies that system components interact temporally in a way that maximizes the benefits of these interactions. Logic dictates that the opportunities for synergy and synchrony are likely to be enhanced in systems of greater diversity, however direct evidence is somewhat scarce.

Despite the appeal of the idea that diverse systems should be more stable, ecologists are still struggling with just how important diversity is for the productivity and stability of natural ecosystems. It may strike some agricultural scientists as surprising that Tilman's recent studies of natural grasslands (e.g., Tilman and Downing, 1994; Tilman et al., 1996; Tilman et al., 1997) provide some of the first experimental evidence from field studies for a link between plant diversity, productivity, and system stability in natural ecosystems. In fact, before Tilman's work, many ecologists cited agricultural experiments comparing monocultures with multiple cropping systems as indicating the importance of diversity for natural ecosystems.

Recent ecological research on diversity indicates that diverse natural communities may be more productive than simple systems (Tilman et al., 1996), just as many agricultural studies have shown significant yield increases in diverse cropping systems compared to monocultures (Trenbath, 1974, 1976; Francis, 1989; Vandermeer, 1989). Overyielding in diverse cropping systems may result from a variety of mechanisms, such as more efficient use of resources (light, water, nutrients) or reduced pest damage, and there have been numerous experimental studies examining these mechanisms.

The mechanisms that result in higher productivity in diverse grassland systems are less well understood, but reduced nitrate losses from diverse systems suggest that increased nitrogen use efficiency may be one important mechanism (Tilman et al., 1996). In cropping systems, when interspecific competition for a limiting factor is less than intraspecific competition for that factor, then overyielding is predicted (Francis, 1989). Facilitation occurs when one crop modifies the environment in a way that benefits a second crop, for example by lowering the population of a critical herbivore or releasing nutrients that can be taken up by the second crop (Vandermeer, 1989). Facilitation may result in overyielding even where direct competition between crops is substantial.

Ecological studies suggest that more diverse plant communities are more resistant to disturbance and more resilient in the face of environmental perturbations like drought. That is, the productivity of diverse communities appears to decline less during a drought and to return more quickly to pre-drought levels than is the case for species-poor communities (Tilman and Downing, 1994). A couple of studies have provided evidence of greater yield stability in diverse cropping systems (Rao and Willey, 1980; Francis and Sanders, 1978), suggesting that resistance to environmental perturbation may be higher in these systems.

Rao and Willey (1980) describe three mechanisms that might lead to yield stability in diverse cropping systems. First, when one crop performs poorly, because of drought or pest epidemic for example, the other crop(s) can compensate, using the space and resources made available. Such compensation is obviously not possible if the crops are grown separately. Second, if the yield advantages of intercrops are greater under stress conditions, then yield stability is higher. Finally, where intercropping leads to reduced pest attack, as it often does (Andow, 1991; Power and Flecker, 1996), then greater yield stability may result.

What is the evidence for enhanced yield stability in diverse cropping systems? There are relatively few studies, but the results of the few are striking. Based on 51 intercrops of sorghum and pigeonpea in India, Rao and Willey (1980) reported higher yield stability of intercrops compared with the stability of sorghum and pigeonpea monocultures. Yield stability was measured by calculating coefficients of variation, by computing regressions of yield against an environmental index, and by estimating the probability of crop failure.

Intercrops exhibited greater yield stability according to all criteria: intercrops had lower coefficients of variation than either sorghum or pigeonpea separately; the response of intercrops to environmental change was as stable or more stable than the most stable component crop (sorghum); and the intercrop showed a much lower probability of crop failure than either of the component crops. The probability of crop failure is an estimate of risk and lower values result from both the higher yields of intercrops and the putative yield stability. A similar analysis of yield and income stability conducted for maize/bean systems in Colombia led to a similar conclusion: intercrops were more stable than monocultures, both agronomically and economically (Francis and Sanders, 1978).

Natarajan and Willey (1986) examined the effect of drought on polyculture overyielding by varying water stress on intercrops of sorghum and peanut, millet and peanut, and sorghum and millet. Although total biomass production in both polycultures and monocultures decreased as water stress increased, all of these intercrops overyielded consistently at five levels of moisture availability ranging from 297 to 584 mm of water applied over the cropping season. The rate of overyielding increased with water stress, such that the relative differences in productivity between monocultures and polyculture became more accentuated as stress increased. These data are consistent with the idea that species richness buffers productivity under conditions of environmental variability and that diversity imparts resistance to perturbation (Tilman and Downing, 1994).

Overall, then, we have good reasons for thinking that the temporal and spatial diversification of cropping systems should lead to higher productivity and perhaps to greater stability.

As a result, there is a persistent conviction among many agroecologists that species-rich natural ecosystems should provide us with models for the design of sustainable agricultural systems (e.g., Hart, 1980; Jackson, 1985; Soule and Piper, 1992). Jackson (1985) and colleagues (e.g., Soule and Piper, 1992) at the Land Institute in Salina, Kansas have promoted the idea that agriculture in the US plains should mimic natural prairies by emphasizing polycultures of herbaceous perennials. Hart (1980) suggested that agricultural systems for the tropics should be designed as analogs of humid tropical forests. Many others have recognized the structural and functional similarity between diverse home gardens in the tropics and humid tropical forests. It remains to be seen, however, whether the 'natural systems mimicry' approach can really lead to useful improvements in the productivity and sustainability of agroecosystems.

2. Agriculture and biodiversity

We know that agricultural practices have significant effects on natural ecosystems and often contribute to the loss of biological diversity (Matson et al., 1997). The loss of biodiversity is increasingly recognized to have a range of negative ecological and societal consequences. There are two dominant approaches to conserving biodiversity in agricultural landscapes. The first, more traditional approach isolates a patch of remaining natural area and protects it from the incursions of human activities through the formation of a nature reserve or park. More sophisticated versions of this approach designate a core zone that will be fully protected and a buffer zone in which some economic activities such as agroforestry will be allowed (Batisse, 1997). This strategy for biodiversity conservation is necessarily limited to those increasingly rare areas where natural areas remain reasonably intact, yet these areas make up only about 5% of the terrestrial environment (Western and Pearl, 1989).

One argument used by many proponents of conventional, high input agricultural systems is that the higher yields assumed to derive from such systems will require that less land be put into production and therefore will relieve the pressure to cultivate remaining natural areas and reserves in the landscape. However, both parts of this argument are open to question. First, the hypothesis that high input systems will necessarily perform better in terms of long-term yields is still a controversial point. For example, Pingali et al. (1997) argue that agricultural intensification has led to serious environmental degradation in many of the high-potential irrigated rice producing regions of Asia and that this degradation is already having negative impacts on rice yields. Long-term experiments on paddy rice production show declining rice yields at constant input rates despite the use of the best cultivars and management practices (Cassman et al., 1994). In farmers fields, yield declines are likely to be masked by increasing input levels, where such inputs are economically feasible. Thus, increasing evidence suggests that yields from highly intensified production systems are unlikely to be sustainable.

Second, there is no convincing evidence to date to support the notion that increasing the productivity of agricultural systems will protect neighboring natural areas. To the extent that productivity is enhanced, there may be a concomitant increase in potential economic returns from cultivating new land, and natural areas may become increasingly threatened. This latter point warrants investigation.

A second approach to conserving biological diversity in agricultural landscapes is to promote biodiversity in agricultural systems themselves (Pimentel, 1992; Power, 1996; Perfecto et al., 1996). If this is the desired approach, then sustainable agriculture and agroecological approaches clearly have advantages over conventional agricultural systems. Over the past decade, evidence has been accumulating rapidly that both traditional agricultural systems and improved, sustainable systems retain higher biodiversity than comparable high input systems (e.g., Roger et al., 1991; Perfecto et al., 1996; Power, 1996; Power and Flecker, 1998).

For example, many studies have shown that shaded cacao and coffee plantations support higher levels of biodiversity than full sun plantations grown without shade (e.g., Perfecto et al., 1996; Power and Flecker, 1998). The shaded systems may be either traditional 'rustic' systems in which the understory of native forests are cleared and the crop is planted under the natural forest overstory. Or they may be improved systems in which a few carefully chosen tree species are planted interspersed among the crop. In either case, these shaded systems can offer significant advantages in terms of biodiversity. The full sun systems can be very productive but they achieve their productivity only with high inputs of fertilizers and pesticides. In addition, they remain productive for shorter periods than the traditional systems and trees need to be replaced more often. Thus they require significant inputs of capital throughout their productive life. In many parts of the world where sun coffee and sun cacao have been introduced, there is growing recognition of the costs of this conversion and farmers are returning to the habit of including shade trees in their plantations. Since many of the commonly used shade trees are leguminous, the trees reduce the amount of nitrogen inputs required. In addition, the shade provides significant weed control and, at least in cacao, reduces disease problems (Evans, 1998).

Conservation of biodiversity can provide a number of benefits to agriculture. Within agricultural landscapes, biodiversity can have significant impacts on ecosystem function within agroecosystems and economic returns from the cropping system. Uncultivated species, including wild relatives of crops, are an important source of germplasm for developing new crops and cultivars. Natural areas adjacent to agricultural systems can provide habitat for pollinators and natural enemies of pests (Power, 1996). For example, Thies and Tscharntke (1999) demonstrated recently that rates of parasitism of pest insects and yield losses in oilseed rape were strongly affected by the complexity of European landscapes. In general, parasitism and plant damage were highly correlated with the amount of uncultivated areas, including field margins, fallow fields, grasslands, and forests. Parasitism of the rape pollen beetle by parasitoid wasps in rape fields went from 0% in landscapes with little or no uncultivated area to an average of 40% in landscapes with 50% or more uncultivated area. This example demonstrates the potential for natural pest control through modifications in landscape structure and also provides evidence of the agronomic benefits of biodiversity conservation in the agricultural landscape.

Within the agroecosystem itself, increasing crop diversity through the use of polycultures can augment the resources available to pollinators and to pest natural enemies such as parasitic wasps, resulting in higher populations of these beneficial organisms (Andow, 1991). Clearly, reductions in pesticide use can lead to greater biological diversity, which can contribute to pest control (Jepson, 1989). Minimizing the use of agrochemicals can also result in the preservation of beneficial soil organisms and the maintenance of functional processes such as decomposition and nutrient cycling (Giller et al., 1997). In sum, the conservation of biodiversity within the agroecosystem affects plant and soil processes that can, in turn, affect crop productivity (Giller et al., 1997; Matson et al., 1997).

Research on biodiversity in agricultural landscapes and comparisons between sustainable and conventional agroecosystems have led to a number of clear guidelines for designing agricultural systems that support high levels of biodiversity (Power and Flecker, 1998). For example, we know that:

- higher diversity (genetic, taxonomic, structural, resource) within the cropping system leads to higher diversity in associated biota
- lower use of pesticides leads to higher diversity in associated biota
- increased biodiversity leads to more effective natural pest control and pollination
- increased biodiversity leads to tighter nutrient recycling

As we accumulate more information about the specific relationship between biodiversity, ecosystem processes, and productivity in a variety of agricultural systems, these guidelines can be used to improve their sustainability and conservation value.

3. Transition to sustainable systems

Given what we know about the benefits of moving toward a more sustainable agriculture, how do we get there? McCrae et al. (1990) offer a blueprint for conversion that includes three stages: increased efficiency, substitution of environmentally benign inputs, and system redesign. Many of the practices that are currently being promoted as components of sustainable agriculture fall into the first two categories. Both stages offer clear benefits in terms of lower environmental impacts and can sometimes, but not always, provide economic advantages compared to conventional systems. Moreover, intuition suggests that incremental changes are likely to be more acceptable to farmers than drastic modifications that may be viewed as highly risky. But does the adoption of practices that increase the efficiency of input use or substitute biologically based inputs for agrochemicals really have the potential to lead to redesign of the agricultural system, as McCrae et al. suggest? As discussed below, experience to date is not encouraging on that point.

3.1. INCREASED EFFICIENCY

Two examples may illustrate the benefits and limitations of increasing efficiency as the first stage of conversion to sustainable agriculture. Despite the broad ecological approach advocated by early proponents of integrated pest management (e.g., Stern et al., 1959; van den Bosch et al., 1982), much of the adoption of IPM has consisted of strategies to ‘optimize’ or rationalize pesticide use, such as the use of economic thresholds. These strategies are effective at reducing the amount of pesticides applied, and therefore result in reduced environmental degradation and economic benefits for farmers. Thus the adoption of IPM, even in this most limited fashion, can be considered a success. However, because economic thresholds are explicitly designed to be used with prescriptive measures such as pesticides, by their very nature they cannot lead to the adoption of other, ecologically-based pest management strategies.

Recommendations for banding fertilizers or herbicides similarly fall under the rubric of increasing efficiency. Simple changes in the timing of fertilizer applications can lead to significant environmental benefits while saving farmers money. For example, in the Yaqui Valley of Mexico, 'home' of the Green Revolution for wheat, intensive wheat production relies on extremely high inputs of nitrogen that result in high nitrate losses to freshwater and marine systems and high gaseous losses to the atmosphere. Changes in the timing of N applications along with reductions in the total amount of N applied can result in significantly lower N losses and therefore fewer environmental impacts (Matson et al., 1998). For example, modified timing of applications of 180 kg ha^{-1} N resulted in losses of 48 kg ha^{-1} with 57% recovery by plants, compared to standard applications of 250 kg ha^{-1} that resulted in losses of 70 kg ha^{-1} and only 46% recovery by plants (Matson et al., 1998). At the same time, this reduced level of N application achieved equivalent yields and grain quality compared to the conventional system and therefore has the potential to save farmers 12–17% percent of after-tax profits. Despite these environmental and economic advantages, however, this fine-tuning of input use has little or no potential to move farmers toward an alternative to the high-input wheat monoculture.

The logical extreme of the increased efficiency model is 'precision agriculture'. Precision agriculture uses increasingly available technologies such as soil sensors, remote sensing, and global positioning systems to design input systems that take into account small scale variability in soil and water resources. Fertilizers and other agrochemicals are applied only where required, leading to lower input costs and higher yields, at least in theory. Of course, the cost of the equipment to conduct the analyses, design the variable rate application program, and carry out the applications is beyond the reach of any but the largest farmers. In addition, despite the hype that has surrounded the development of precision agriculture, to date both the environmental and economic benefits to farmers are far from clear.

Clearly, this type of high cost, advanced technology model is inappropriate for most farmers throughout the world. More importantly, like the economic threshold paradigm of IPM, this strategy is explicitly designed around the use of agrochemicals and is highly unlikely to lead to biologically-based ways of coping with variability.

3.2. INPUT SUBSTITUTION

The second stage in McCrae et al.'s (1990) transition to sustainable agriculture is the substitution of environmentally benign inputs for conventional technologies such as pesticides or fertilizers. As Rosset and Altieri (1997) have pointed out, both sustainable agriculture and organic production systems are increasingly relying on input substitution, while largely retaining the structure and function of conventional agricultural systems. Thus a benign 'biological pesticide' like the microbial pathogen *Bacillus thuringiensis* (*B.t.*) is purchased from the same chemical companies that sell the insecticides previously used and is applied using the same spray rigs previously used to apply the insecticides. Botanical insecticides are distinguished from their chemical counterparts by origin, but not necessarily by reduced toxicity or beneficial interactions with other components of the system, and they too may be marketed by agrochemical companies. Commercial compost and purchased manure are similarly substituted for chemical fertilizers.

Initially, many of these biological solutions for pest problems or nutrient deficiencies were developed by public sector researchers, or by farmers themselves, in response to societal demands for healthy food and environmental protection. In many cases, small scale production of these products by individual farmers or communities using local materials is perfectly feasible and has been achieved in a variety of places around the world (Altieri et al., 1997). Microbial biological control agents such as *B.t.* and benign botanical insecticides such as neem oil are good examples. Yet in many localities, production has been largely left to, or taken over by, corporate input suppliers. Thus these biologically based substitutes for agrochemicals may often, if not always, provide health and environmental benefits, but may not necessarily lead to significant modification of the system. Moreover, as they have become commodified they have lost their potential for freeing farmers or communities from their dependence on input suppliers. That is, their 'pro-poor' potential has been lost.

A useful question is whether any input substitutions have the potential to significantly transform system function or structure, and therefore lead to redesign of the agroecosystem. The most promising candidates are probably inputs like green manures, which are clearly substituting for chemical fertilizers but can also have significant effects on soil structure, soil organic matter, water-holding capacity of the soil, and even management of pests, pathogens, and weeds. In long-term cropping system experiments in Pennsylvania, USA, a maize/soybean rotation system using legumes as the source of nitrogen had yields and profits equivalent to the conventional system using commercial N fertilizer (Drinkwater et al., 1998). However, soil organic matter and nitrogen content increased substantially over a 15 year period under the legume system, whereas in the conventional system N content declined and organic matter remained unchanged. In addition, cumulative leaching losses of N were 50% higher in the conventional system. Green manures can also break up pest life cycles and suppress the emergence and growth of weeds. Recent experiments indicate that some of this suppressive effect is due to the enhancement of weed pathogens in green manure systems compared to conventional systems (Liebman and Davis, 2000). 'Transforming' technologies like green manures thus act initially as input substitutions but significantly alter ecosystem function.

3.3. REDESIGN OF THE SYSTEM: SYNDROMES OF PRODUCTION

If we really want to evaluate the ability of sustainable agriculture to maintain and increase productivity, it may be that we need to evaluate systems that have proceeded all the way to system redesign, rather than evaluate the intermediate steps of increased efficiency and substitution. Why? Because of the phenomenon of 'syndromes of production' (Andow and Hidaka, 1989).

One of the paradoxes (and frustrations) of research in sustainable agriculture has been the inability of low-input practices to outperform conventional practices in side-by-side experimental comparisons, despite the success of many organic and low-input production systems in practice (Vandermeer, 1997). A potential explanation for this paradox was offered by Andow and Hidika (1989) in their description of 'syndromes of production.' A production syndrome is a set of management practices that are mutually adaptive and lead to high performance. However, subsets of this collection of practices may be substantially less adaptive; that is, the interaction among practices leads to improved system performance that cannot be explained by the additive effects of individual practices.

This synergistic effect is often identified by practitioners as key to the benefits of sustainable systems (Uphoff, 1999). It may also help to explain why farmers rarely adopt new technologies or practices without modification. This synergy makes it difficult to evaluate individual practices effectively, because experimental tests of individual practices or subsets of practices are unlikely to reveal the true potential of any production syndrome.

Alternative syndromes of production may be likened to peaks of yield (or profit) on an 'adaptive landscape' (*sensu* Wright, 1932) of management practices, such that moving to another, higher peak on the landscape requires traveling through non-adaptive valleys (Figure 1). Thus system performance may decline as farmers attempt the transition from conventional to sustainable systems, particularly if they adopt sustainable practices one by one.

Andow and Hidaka (1989) illustrate the concept of production syndromes with a comparative study of two types of Japanese rice production: conventional, high input production and the shizeñ or 'natural' farming system which has become widely known through the efforts of Fukuoka (1978). Although rice yields were comparable in the two systems, management practices differed in almost every respect: irrigation practice, transplanting technique, plant density, fertility source and quantity, and management of insects, diseases and weeds. Andow and Hidaka (1989) argue that systems like shizeñ function in a qualitatively different way

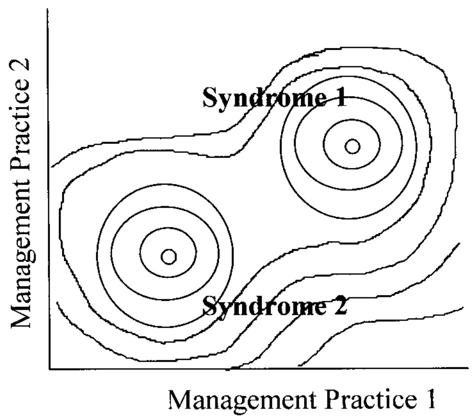

Figure 1. Production syndromes plotted in two dimensions of management practices (after Andow and Hidaka, 1989). Contour lines represent a third variable, a measure of success such as yield, which peaks where the two management practices together produce highest yields. A small deviation in either management practice results in a move away from the peak and therefore a decline in yield. A more accurate representation of the production syndrome would involve many more management dimensions.

than conventional systems. This array of cultural practices and pest management practices result in functional differences that cannot be accounted for by any single practice.

It is likely that there are other rice production syndromes that lead to high performance. The management practices that make up the rice intensification system (SRI) of Madagascar (Uphoff 1999) are distinctly different from those used by either conventional rice production or shizeñ farming (Andow and Hidaka 1989), and it is possible that these practices would form another peak on the rice production landscape.

4. Conclusions

Although the sustainable agriculture movement has largely concentrated on increasing the efficiency of the use of external inputs and on the substitution of environmentally benign inputs, it is through the redesign of agricultural systems that breakthroughs in productivity are likely to take place. It may be through the development and adaptation of production syndromes that the full benefits of sustainable agriculture practices will be realized. Our next task is to identify a variety of production syndromes that could be usefully adapted and lead to higher productivity in many less-industrialized countries. To the extent that these alternative production syndromes include higher levels of plant diversity, biodiversity conservation may also be enhanced.

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