Chapter 2: Agroecology and Agroecosystems

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Introduction

Agriculture is more than an economic activity designed to produce a crop or to make as large a profit as possible on the farm. A farmer can no longer only pay attention to the objectives and goals for his or her farm and expect to adequately deal with the concerns of long-term sustainability. Discussions about sustainable agriculture must go far beyond what happens within the fences of any individual farm. Farming is now viewed as a much larger system with many interacting parts, including environmental, economic, and social components (Gliessman, 2001; Flora, 2001). It is the complex interactions and balance among all of these parts that have brought us together to discuss sustainability, determine how we move towards this broader goal, and how an agroecological perspective focused on sustainable agroecosystems is a way to achieve such long term objectives.

Much of modern agriculture has lost the balance needed for long-term sustainability (Kimbrell, 2002). With their excessive dependence on fossil fuels and external inputs, most industrialized agroecosystems are overusing and degrading the soil, water, genetic, and cultural resources upon which agriculture has always relied. Problems in sustaining agriculture's natural resource foundation can only be masked for so long by modern practices and high input technologies. In a sense, as we borrow ever-increasing amounts of water and fossil fuel resources from future generations, the negative impacts on farms and farming communities will continue to become more evident. The conversion to sustainable agroecosystems must become our goal (Gliessman, 2001).

In an attempt to clarify my own thinking about agroecosystems, I often think of agriculture as a stream, and farms are different points along that stream. When we think of an individual farm as a "pool" in a calm eddy at some bend in the stream's flow, we can imagine how many things "flow" into a farm, and we also expect that many things "flow" out of it as well. As a farmer, I work hard to keep my pool in the stream (my farm) clean and productive. I try to be as careful as possible how I care for the soil, which crops I plant, how I control pests and diseases, and how I market my harvest. Back in the days when there weren't as many farms, fewer people to feed, and smaller demands on farmers and farmland, I could keep my farm in pretty good shape. I could keep my "pool" in the stream pretty clean, and did not have to worry very much about what was going on "downstream" from my farm.

But such a strategy has become much more difficult today. I find that I have less and less control over what comes into my "pool." I face a variety of "upstream impacts" that in combination can threaten the sustainability of my farm. This includes the inputs into my farm that either I purchase or which arrive from the surrounding area. They include labor availability and cost, market access for what I produce, legislated policies that determine how much water I use, pesticides I apply, or how I care for my animals, not to mention the vagaries of the weather! My pool can become quickly muddied.

I must also increasingly consider that the way I take care of my “pool” can have "downstream effects" in the stream below. Soil erosion and groundwater depletion can negatively affect other farms than my own. Inappropriate or inefficient use of pesticides and fertilizers can contaminate the water and air, as well as leave potentially harmful residues on the food that my family and others will consume. How well I do on my farm is reflected in the viability of rural farm economies, our local community, and cultures broadly. Key indicators are the losses of farm land to other activities and the loss of family farms in general. Both upstream and downstream factors are linked in complex ways, often beyond my control, and they impinge upon the sustainability of my farm.

The Agroecology Perspective

A. The Agroecosystem

Any definition of sustainable agriculture must include how we examine the production system as an agroecosystem. We need to look at the entire system, or the entire "stream" using the analogy introduced above. This definition must move beyond the narrow view of agriculture that focuses primarily on the development of practices or technologies designed to increase yields and improve profit margins. These practices and technologies must be evaluated on their contributions to the overall sustainability of the farm system. The new technologies have little hope of contributing to sustainability unless the longer-term, more complex impacts of the entire agricultural system are included in the evaluation. The agricultural system is an important component of the larger food system (Francis et al., 2003).

A primary foundation of agroecology is the concept of the ecosystem, defined as a functional system of complementary relations between living organisms and their environment, delimited by arbitrarily chosen boundaries, which in space and time appears to maintain a steady yet dynamic equilibrium (Odum, 1996; Gliessman, 1998). Such an equilibrium can be considered to be sustainable in a definitive sense. A well-developed, mature natural ecosystem is relatively stable, self-sustaining, recovers from disturbance, adapts to change, and is able to maintain productivity using energy inputs of solar radiation alone. When we expand the ecosystem concept to agriculture, and consider farm systems as agroecosystems, we have a basis for looking beyond a primary focus on traditional and easily measured system outputs (yield or economic return). We can instead look at the complex set of biological, physical, chemical, ecological, and cultural interactions determining the processes that permit us to achieve and sustain yields.

Agroecosystems are often more difficult to study than natural ecosystems because they are complicated by human management which alters normal ecosystem structures and functions. There is no disputing the fact that for any agroecosystem to be fully sustainable, a broad series of interacting ecological, economic, and social factors and processes must be taken into account. Still, ecological sustainability is the building block upon which other elements of sustainability depend.

An agroecosystem is created when human manipulation and alteration of an ecosystem take place for the purpose of establishing agricultural production. This introduces several changes in the structure and function of the natural ecosystem (Fig. 1), and as a result, changes in a number of key system level qualities. These qualities are often referred to as the emergent qualities or properties of systems – qualities that manifest themselves once all of the component parts of the system are organized. These same qualities can also serve as indicators of agroecosystem sustainability (Gliessman, 2001). Some of the key emergent qualities of ecosystems, and how they are altered as they are converted to agroecosystems, are as follows:

1. Energy Flow

Energy flows through a natural ecosystem as a result of complex sets of trophic interactions, with certain amounts being dissipated at different stages along the food chain, and with the greatest amount of energy within the system ultimately moving along the detritus pathway (Odum, 1971). Annual production of the system can be calculated in terms of net primary productivity or biomass, each component with its corresponding energy content. Energy flow in agroecosystems is altered greatly by human interference (Rappaport, 1971; Pimentel and Pimentel, 1997). Although solar radiation is obviously the major source of energy, many inputs are derived from human-manufactured sources and are most often not self-sustaining. Agroecosystems too often become through-flow systems, with a high level of fossil fuel input and considerable energy directed out of the system at the time of each harvest. Biomass is not allowed to otherwise accumulate within the system or contribute to driving important internal ecosystem processes (e.g. organic detritus returned to the soil serving as an energy source for microorganisms that are essential for efficient nutrient cycling). For sustainability to be attained, renewable sources of energy must be maximized, and energy must be supplied to fuel the essential internal trophic interactions needed to maintain other ecosystem functions.

2. Nutrient Cycling

Small amounts of nutrients continually enter an ecosystem through several hydrogeochemical processes. Through complex sets of interconnected cycles, these nutrients then circulate within the ecosystem, where they are most often bound in organic matter (Borman and Likens, 1967). Biological components of each system become very important in determining how efficiently nutrients move, ensuring that minimal amounts are lost from the system. In a mature ecosystem, these small losses are replaced by local inputs, maintaining a nutrient balance. Biomass productivity in natural ecosystems is linked very closely to the annual rates at which nutrients are able to be recycled. In an agroecosystem, recycling of nutrients can be minimal, and considerable quantities are lost from the system with the harvest or as a result of leaching or erosion due to a great reduction in permanent biomass levels held within the system (Tivy, 1990). The frequent exposure of bare soil between crop plants during the season, or from open fields between cropping seasons, creates "leaks" of nutrients from the system. Modern agriculture has come to rely heavily upon nutrient inputs derived or obtained from petroleum-based sources to replace these losses. Sustainability requires that these “leaks” be reduced to a minimum and recycling mechanisms be reintroduced and strengthened. Ultimately, human societies need to find ways to return nutrients consumed in agricultural products back to the fields – the agroecosystems that consumed andproduced them in the first place.

3. Population Regulating Mechanisms

Through a complex combination of biotic interactions and limits set by the availability of physical resources, population levels of the various organisms are controlled, and thus eventually link to and determine the productivity of the ecosystem. Selection through time tends toward the establishment of the most complex structure biologically possible within the limits set by the environment, permitting the establishment of diverse trophic interactions and niche diversification. Due to human-directed genetic selection and domestication, as well as the overall simplification of agroecosystems (i.e. the loss of niche diversity and a reduction in trophic interactions), populations of crop plants or animals are rarely self-reproducing or self-regulating. Human inputs in the form of seed or control agents, often dependent on large energy subsidies, determine population sizes. Biological diversity is reduced, natural pest control systems are disrupted, and many niches or microhabitats are left unoccupied. The danger of catastrophic pest or disease outbreak is high, often despite the availability of intensive human interference and inputs. A focus on sustainability requires the reintroduction of the diverse structures and species relationships that permit the functioning of natural control and regulation mechanisms. We must learn to work with and profit from diversity, rather than focus on agroecosystem simplification.

4. Dynamic Equlibrium

The species richness or diversity of mature ecosystems permits a degree of resistance to all but very damaging perturbations. In many cases, periodic disturbances ensure the highest diversity, and even highest productivity (Connell, 1978). System stability is not a steady state, but rather a dynamic and highly fluctuating one which permits ecosystem recovery following disturbance. This promotes the establishment of an ecological equilibrium that functions on the basis of sustained resource use which the ecosystem can maintain indefinitely, or can even shift if the environment changes. At the same time, rarely do we witness what might be considered large-scale disease outbreaks in healthy, balanced ecosystems. But due to the reduction of natural structural and functional diversity, much of the resilience of the system is lost, and constant human-derived external inputs must be maintained. An over-emphasis on maximizing harvest outputs upsets the former equilibrium, and can only be maintained if such outside interference continues. To reintegrate sustainability, the emergent qualities of system resistance and resiliency must once again play a determining role in agroecosystem design and management.

We need to be able to analyze both the immediate and future impacts of agroecosystem design and management so that we can identify the key points in each system on which to focus the search for alternatives or solutions to problems. We must learn to be more competent in our agroecological analysis in order to avoid problems or negative changes before they occur, rather than struggle to reverse the problems after they have been created. The agroecological approach provides us one such alternative (Altieri, 1995; Gliessman, 1998).

B. Applying Agroecology

The process of understanding agroecosystem sustainability has its foundations in two kinds of ecosystems: natural ecosystems and traditional (also known as local or indigenous) agroecosystems. Both provide ample evidence of having passed the test of time in terms of long-term productive ability, but each offers a different knowledge base from which to understand this ability. Natural ecosystems are reference systems for understanding the ecological basis for sustainability in a particular location. Traditional agroecosystems provide many examples of how a culture and its local environment have co-evolved over time through processes that balance the needs of people, expressed as ecological, technological, and socio-economic factors. Agroecology, defined as the application of ecological concepts and principles to the design and management of sustainable agroecosystems (Gliessman, 1998), draws on both to become a research approach that can be applied to converting unsustainable and conventional agroecosystems to sustainable ones.

Natural ecosystems reflect a long period of evolution in the use of local resources and adaptation to local ecological conditions. They have each become complex sets of plants and animals that co-inhabit in a given environment, and as a result, provide extremely useful information for the design of more locally adapted agroecosystems. As I have suggested (Gliessman, 1998), "the greater the structural and functional similarity of an agroecosystem to the natural ecosystems in its biogeographical region, the greater the likelihood that the agroecosystem will be sustainable." If this suggestion holds true, natural ecosystem structures and functions can be used as benchmarks or threshold values for more sustainable systems. Scientists have begun to explore how an understanding of natural ecosystems can be used to guide our search for sustainable agroecosystems that respect and protect the environment and natural resources (Soule and Piper, 1992; Jackson and Jackson, 2002).

Traditional and indigenous agroecosystems are different from conventional systems in that they developed originally in times or places where inputs other than human labor and local resources were generally not available or desirable to the local people. Production takes place in ways that demonstrate people's concerns about long-term sustainability of the system, rather than solely maximizing output and profit. Traditional systems continue to be important as the primary producers of food for a large part of the populations of many developing countries, while at the same time maintaining their foundations in ecological knowledge (Wilken, 1988; Altieri, 1990). This reality demonstrates their importance for the development of sustainable agroecosystems. This is especially true today when so many modern conventional agroecosystems have caused severe degradation of their ecological foundations, as socio-economic factors have become the predominant forces in the food system (Altieri, 1990). Many traditional agroecosystems are actually very sophisticated examples of the application of ecological knowledge, and can serve as the starting point for the conversion to more sustainable agroecosystems in the future. The traditional Mesoamerican intercrop of corn, beans, and squash is a well-known cropping system where higher yields in the mixtures come about due to a complex of interactions among components of the agroecosystem (Amador and Gliessman, 1990). Examples of such interactions range from the increased presence of beneficial insects due to attractive microclimates and a greater abundance of pollen and nectar sources (Letourneau, 1986), to biologically fixed nitrogen being made available to corn through mycorrhizal fungi connections with roots of beans (Bethlenfalvay et al., 1991).

How can agroecology link our understanding of natural ecosystem structure and function with the knowledge inherent in traditional agroecosystems? On the one hand, the knowledge of place that comes from understanding local ecology is an essential foundation. Another is the local experience with farming that has its roots in many generations of living and working within the limits of that place. We put both of these approaches together when we work with farmers going through the transition process to more environmentally sound management practices, and thus realize the potential for contributing to long term sustainability. This transition is already occurring. Many farmers, despite the heavy economic pressure on agriculture, are in the process of converting their farms to more sustainable design and management (National Research

Council 1989, USDA, 2000). In California the dramatic increase in organic acreage for a range of crops has been based largely on farmer innovation (Swezey and Broome, 2000). It is incumbent that agroecologists play an important role in contributing to this conversion process.

Converting an agroecosystem to a more sustainable design is a complex process. It is not just the adoption of a new practice or a new technology. There are no silver bullets. Instead, this conversion uses the agroecological approach described above. The farm is perceived as part of a larger system of interacting parts - an agroecosystem. We must focus on redesigning that system in order to promote the functioning of an entire range of different ecological processes (Gliessman, 1998). In a study of the conversion of conventional strawberries to organic management, several changes were observed (Gliessman et al., 1996). As the use of synthetic chemical inputs was reduced or eliminated, and recycling was emphasized, agroecosystem structure and function changed as well. A range of processes and relationships began to transform, beginning with improvement in basic soil structure, an increase in soil organic matter content, and greater diversity and activity of beneficial soil biota. Major changes began to occur in the activity and relationships among weed, insect, and pathogen populations, and in the functioning of natural control mechanisms. For example, predatory mites gradually replaced the use of synthetic acaracides for the control of two-spotted spider mites, the most common arthropod pest in strawberries in California.

Ultimately, nutrient dynamics and cycling, energy use efficiency, and overall agroecosystem productivity are affected. Changes may be required in day-to-day management of the farm, planning, marketing, and even philosophy. The specific needs of each agroecosystem will vary, but the principles for conversion listed in Table 1 can serve as general guidelines for working through the transition. It is the role of the agroecologist to help the farmer measure and monitor these changes during the conversion period in order to guide, adjust, and evaluate the conversion process. Such an approach provides an essential framework for determining the requirements for and indicators of sustainable agroecosystem design and management.

C. Comparing Ecosystems and Agroecosystems

The key to developing sustainability is building a strong ecological foundation under the agroecosystem, using the ecosystem knowledge of agroecology described above. This foundation then serves as the framework for producing the sustainable harvests needed by humans. In order to maintain sustainable harvests, though, human management is a requirement. Agroecosystems are not self-sustaining, but rely on natural processes for maintenance of their productivity. Agroecosystem resemblance to natural ecosystems allows the system to be sustained, in spite of the long-term human removal of biomass, without large subsidies of non-renewable energy and without detrimental effects on the surrounding environment.

Table 2 compares natural ecosystems with three types of agroecosystems in terms of several ecological criteria. Traditional agroecosystems most closely resemble natural ecosystems, since they most often are focused on the use of locally available and renewable resources, local use of agricultural products, and the return of biomass to the farming system. Sustainable agroecosystems are very similar in many properties, but due to the probable focus on export of harvest to distant markets, the need to purchase a significant part of their nutrients externally, and the much stronger impact of market systems on agroecosystem diversity and management, they are more dissimilar in others. Compared to conventional systems, sustainable agroecosystems have somewhat lower and more variable yields due to the weather variation that occurs from year to year. Such reductions in yields can be more than offset, from the perspective of sustainability, through the advantages gained in reduced dependence on external inputs, more reliance on natural controls of pests, and reduced negative impacts of farming activities off the farm.

Future Perspectives

Problems in agriculture create the pressures for the changes which will bring about a sustainable agriculture. But it is one thing to express the need for sustainability, and yet another to actually quantify it and bring about the changes that are required. Designing and managing sustainable agroecosystems, as an approach, is in its formative stages. It builds initially upon the fields of ecology and agricultural science, and emerges as the science of agroecology. This combination can play an important role in developing the understanding necessary for a transition to sustainable agriculture.

But sustainable agriculture is more. It takes on a cultural perspective as the concept expands to include humans and their impact on agricultural environments. Agricultural systems are a result of the co-evolution that occurs between culture and environment, and a sustainable agriculture values the human as well as the ecological components. Our small "pool" in the "stream" becomes the focal point for changing how we do agriculture, but that change must occur in the context of the human societies within which agriculture is practiced, the whole stream in this analogy.

All agricultural systems can no longer be viewed as strictly production activities driven primarily by economic pressures. We need to reestablish an awareness of the strong ecological foundation upon which agriculture originally developed and ultimately depends. Too little importance has been given to the "downstream" effects that are manifest off the farm, either by surrounding natural ecosystems or by human communities. We need an interdisciplinary basis upon which to evaluate these impacts.

In the broader context of sustainability, we must study the environmental background of the agroecosystem, as well as the complex of processes involved in the maintenance of long-term productivity. We must first establish the ecological basis of sustainability in terms of resource use and conservation, including soil, water, genetic resources, and air quality. Then we must examine the interactions among the many organisms of the agroecosystem, beginning with interactions at the individual species level, and culminating at the ecosystem level as our understanding of the dynamics of the entire system is revealed.

Our understanding of ecosystem level processes should then integrate the multiple aspects of the social, economic and political systems within which agroecosystems function, making them even more complex systems. Such an integration of ecosystem and social system knowledge about agricultural processes will not just lead to a reduction in synthetic inputs used for maintaining productivity. It will also permit the evaluation of such qualities of agroecosystems as the long-term effects of different input/output strategies, the importance of the environmental services provided by agricultural landscapes, and the relationship between economic and ecological components of sustainable agroecosystem management. By properly selecting and understanding the "upstream" inputs into agriculture, we can be ensured that what we send "downstream" will promote a sustainable future.

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Table 1. Guiding Principles for the process of conversion to sustainable agroecosystems design and management (Modified from Gliessman, 1998).

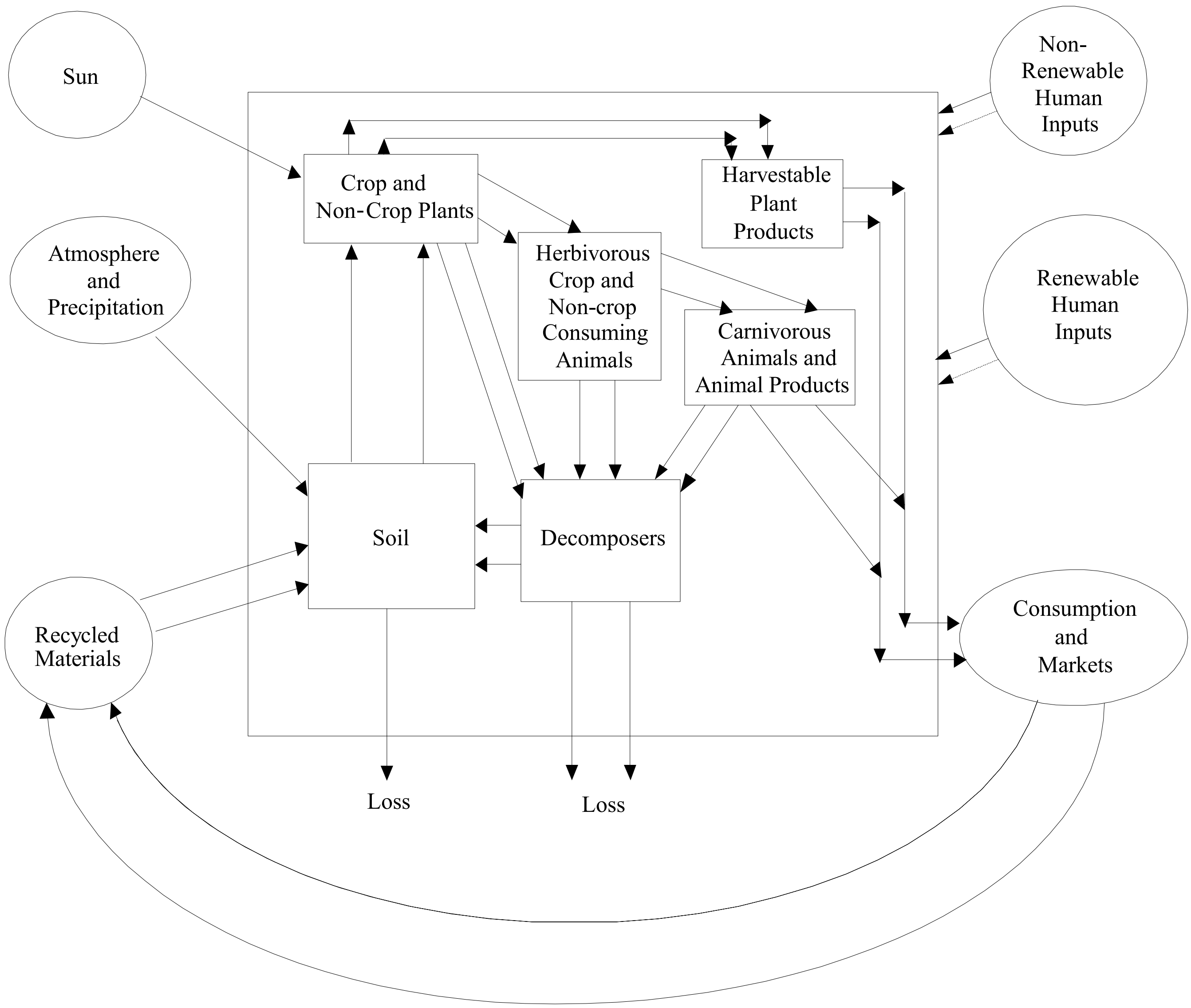
- Shift from throughflow nutrient management to recycling of nutrients, with increased dependence on natural processes such as biological nitrogen fixation and mycorrhizal relationships.
- Use renewable sources of energy instead of non-renewable sources.
- Eliminate the use of non-renewable off-farm human inputs that have the potential to harm the environment or the health of farmers, farm workers, or consumers.
- When materials must be added to the system, use naturally-occurring materials instead of synthetic, manufactured inputs.
- Manage pests, diseases, and weeds instead of "controlling" them.
- Reestablish the biological relationships that can occur naturally on the farm instead of reducing and simplifying them.
- Make more appropriate matches between cropping patterns and the productive potential and physical limitations of the farm landscape.
- Use a strategy of adapting the biological and genetic potential of agricultural plant and animal species to the ecological conditions of the farm rather than modifying the farm to meet the needs of the crops and animals.
- Value most highly the overall health of the agroecosystem rather than the outcome of a particular crop system or season.
- Emphasize conservation of soil, water, energy, and biological resources.
- Incorporate the idea of long-term sustainability into overall agroecosystem design and management.

Table 2. Emergent properties of natural ecosystems, traditional agroecosystems, conventional agroecosystems, and sustainable agroecosystems. Agroecosystem properties are most applicable to the farm scale and for the short- to medium-term time frame.

Emergent Ecological Property	Natural Ecosystem	Agroecosystem Type		
		Traditional	Conventional	Sustainable
Productivity (process)	Medium	Medium	Low/med.	Med./high
Species diversity	High	Med./high	Low	Medium
Structural diversity	High	Med./high	Low	Medium
Functional diversity	High	Med./high	Low	Med./high
Output stability	Medium	High	Low/med.	High
Biomass accumulation	High	High	Low	Med./high
Nutrient recycling	High	High	Low	High
Trophic relationships	High	High	Low	Med./high
Natural Population regulation	High	High	Low	Med./high
Resistance	High	High	Low	Medium
Resilience	High	High	Low	Medium
Dependence on external human inputs	Low	Low	High	Medium
Autonomy	High	High	Low	High
Human displacement of ecological processes	Low	Low	High	Low/med.
Sustainability	High	Med./high	Low	High

Modified from Odum (1984), Conway (1985), Altieri (1995), and Gliessman (1998).

Fig. 1. Functional and structural components of an ecosystem converted to a sustainable agroecosystem. Solid lines are energy flow, and dotted lines are nutrient cycles. This model assumes that nutrients and leftover energy are returned to the agroecosystem as reusable materials, and that the use of non-renewable human inputs is minimized.



Chapter 2 Study Questions

1. What kinds of changes need to be made in the design and management of agroecosystems so that we can come closer to farming in "nature's image'?

2. Describe a characteristic or component of a traditional farming system that would find widespread application in conventional farming systems if sustainability were a primary goal.

3. What are some of the primary key variables that determine the length of time necessary for converting a farm from non-sustainable to sustainable management?

4. What do you feel are the key differences in how nutrient cycles operate in natural ecosystems as compared to conventional agroecosystems, and how you would take these differences into account in developing a more sustainable design and management strategy for agriculture?

5. What is meant by achieving "level 3" in the process of conversion to more sustainable agroecosystem research and development? Give an example of a change you would incorporate into a cropping system of your choice that demonstrates your knowledge of the concept.