

## 2 The Human Ecology Perspective

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The term "human ecology" has had many meanings when used in different disciplines by different scientists at different points in the history of their disciplines. In this book the human ecology of agroecosystems is concerned with understanding how farms function. It is a way of looking at agriculture as a whole system—agricultural fields and the people who farm them. Agricultural fields are ecosystems (agroecosystems) with a large number of interacting and interdependent physical and biological components. Farmers are part of a human social system. Agroecosystems interact with adjoining ecosystems and with the social systems of the people who farm them (Figure 2.1). The way agroecosystems function, including their production of goods and services for human welfare, is a consequence of these interactions (Rambo 1982, Rambo and Sajise 1985). How each part of a farm functions can be fully understood only in the context of the whole, that is, how that part fits in with the rest of the farm.

Human ecology provides the holism needed to comprehend interactions between agroecosystems and human social systems. This is the same kind of holism that farmers live with in managing their farm enterprises, and it has long been a part of farm management science, as reflected in terms such as "integrated farming" and "farming systems" (Dalton 1975, Gilbert et al. 1980, Harwood 1979, Ruthenberg 1971, Shaner et al. 1981, 1982). The human ecology approach in this book has two major thrusts:

1. It emphasizes the numerous ecological processes within an agroecosystem that determine how the agroecosystem functions as a whole (Cox and Atkins 1979, Mitchell 1979, Hart 1980, Bayliss-Smith 1982, Altieri 1983, Lowrance et al. 1984); and
2. It emphasizes the numerous points of interaction between agroecosystems and human social systems (Rambo 1982).

Interactions between agroecosystems and human social systems involve exchanges of energy, materials, and information within and between the two systems (Figure 2.1). The passage of energy, materials, and information

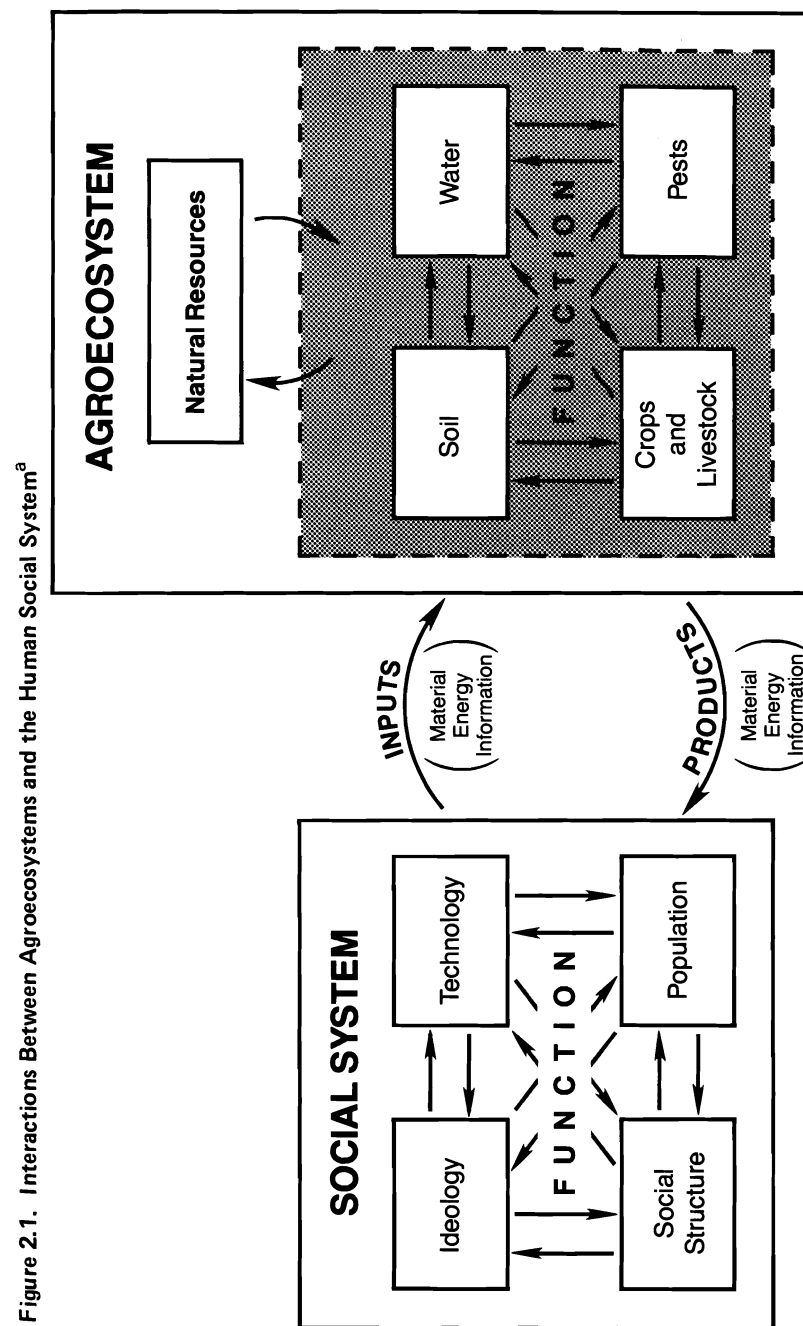


Figure 2.1. Interactions Between Agroecosystems and the Human Social System<sup>a</sup>

Source: Modified from Rambo 1982.

<sup>a</sup> "Natural Resources" in the diagram are soil, water, and biological resources from which agroecosystems are constructed.

from a human social system to an agroecosystem takes the form of human activities and inputs to the agroecosystem that shape its structure and ultimately how it functions. The passage of energy, materials, and information from the agroecosystem to the social system consists primarily of the products and services provided by the agroecosystem. The exchange also includes perceptual information that farmers obtain about how their agroecosystems are functioning, to aid in their decisions on structuring their agroecosystems.

Understanding these exchanges of matter, energy, and information between the two systems makes it possible to appreciate how the behavior of each is shaped by the other through repercussions of events or actions in the coupled system. A comprehension of how the two systems interact also makes it possible to appreciate how agroecosystems and human social systems adjust to one another. Studying the human ecology of agroecosystems can be valuable to agricultural scientists by helping them to design new agricultural systems with *ecological viability* based on an appreciation of agroecosystem processes and with *social viability* based on an appreciation of the combined agroecosystem-social system.

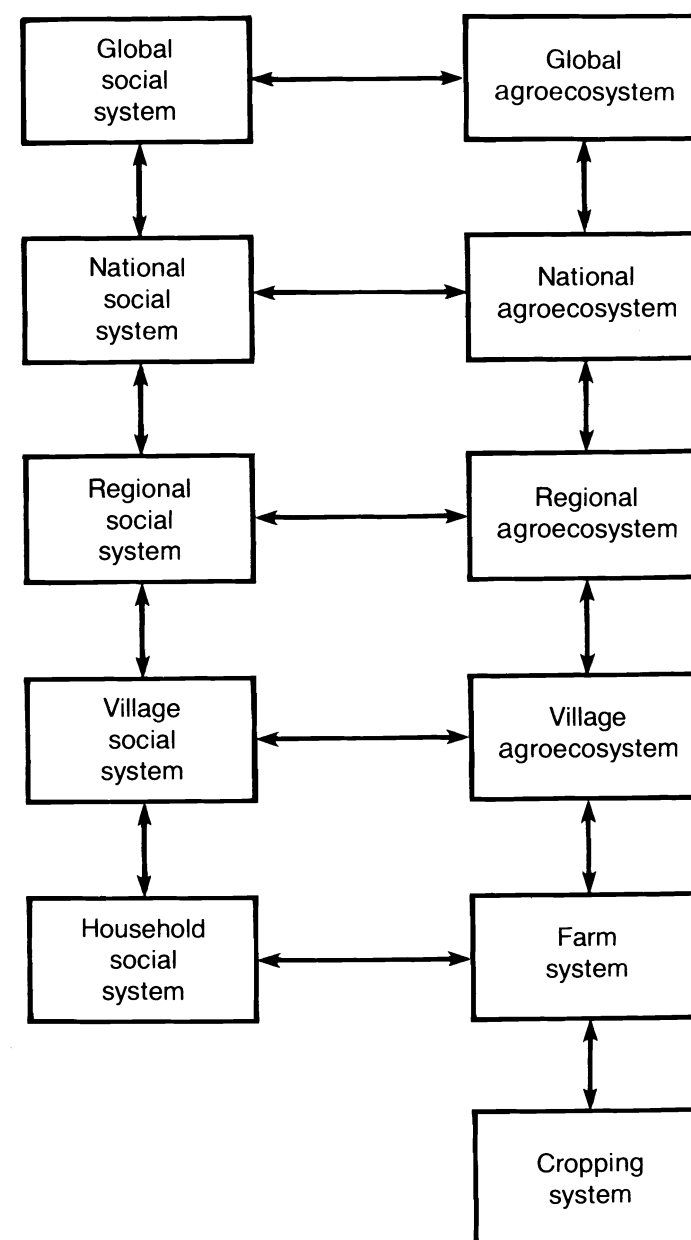
Agroecosystems and social systems can interact in a range of scales (Figure 2.2). A few square meters of farm land are an ecosystem, and so is an entire continent. Human social systems can be households, villages, ethnic groups, nations, and the international community of nations. This book will focus on human social systems primarily at the household level. It will focus on agroecosystems at two levels:

1. The *cropping system*, a particular configuration of crops in space and time that is employed more or less homogeneously on a single agricultural field; and
2. The *farm system*, the array of one or more cropping systems employed by a single farm household.

A farm household as a social unit makes decisions on the cropping systems it will employ, and how they will be structured and combined to form the household farm system. One household also may have an influence on the farm systems of other households as a consequence of its social interactions with those households. The sum of all these interactions (i.e., the village social system) is a major determinant of the village-level agroecosystem (i.e., the array of cropping systems in the village). The "outer world" (the social system beyond the village) also can have an impact on the farm systems selected by individual households and the village. Markets, new technologies, government educational activities, and outside cultures may compel local households to change the way they conduct their lives, including the way they structure their agroecosystems and interact with them.

This chapter describes the major elements of structure and function in agroecosystems of small-scale subsistence farmers in Southeast Asia and provides examples of interactions between farmers and the agroecosystems on which they depend for a living. Other chapters in the book explore

Figure 2.2. An Organizational Hierarchy for Agroecosystems and Human Social Systems



the nature of those interactions in further detail, emphasizing the traditional agriculture that still prevails in many areas and exploring the numerous changes taking place in the social systems and agroecosystems of traditional farmers.

## AGROECOSYSTEM STRUCTURE

Land, water, sunlight, and living organisms are the natural resources on which agroecosystems are based. Land varies enormously in its suitability for agriculture in general and for different kinds of agriculture in particular. Soil quality for agriculture depends upon its drainage, its capacity for storing mineral nutrients and water, and the quantity of nutrients and water actually present or available in the soil for the crops. The soil's capacity for storage of both moisture and nutrients is increased by a finer texture in its mineral particles (i.e., more clay) and a higher quantity of organic matter. A highly weathered, sandy soil that is low in organic matter and has had most of its mineral nutrients leached away is suitable only for the relatively few crops (e.g., cassava) that tolerate low fertility and high moisture stress; a highly fertile soil with abundant and reliable supplies of soil moisture and mineral nutrients is suitable for a great variety of crops. Extremes of soil texture, such as heavy clay soils with drainage problems, or extremes of soil organic matter, such as highly acidic peat soils, can also limit crop productivity and the choice of crops suitable for cultivation.

Water, as a major resource for crop growth, significantly conditions the structure and function of agroecosystems, because even in humid regions uneven rainfall distribution can be a serious constraint on crop growth at certain times of the year. The amount of rainfall may be highly variable from week to week and from year to year, and farmers must adjust cropping systems to droughts of several weeks in the middle of a growing season, or to growing seasons in which total rainfall is well below normal.

One of the main characteristics distinguishing agricultural ecosystems from natural ecosystems is the primary role that human activities have in shaping the structure and function of agroecosystems. The structure of any ecosystem can be characterized in terms of its component parts—the soil, water, and numerous species of living organisms (plants, animals, microorganisms) it contains—and how they are all arranged in space and time. Farmers structure their agroecosystems to provide desired goods and services.

Agroecosystems contain one or more biological components (crops and livestock) intended to provide products for human consumption, but they also contain numerous other species of living organisms that can affect how the agroecosystem functions from a human perspective. Some organisms act as pests that compete with crops for light, water, or mineral nutrients or feed upon the crops as herbivores, parasites, or pathogens. Other organisms are essential to sustaining crop production on a long-term basis because of their roles in vital ecosystem processes. For example, soil animals, fungi, and bacteria are essential to the maintenance of soil fertility because of

their role in biological decomposition that releases mineral nutrients into the soil. Other animals and microorganisms are natural enemies of crop pests, preventing the pests from becoming abundant enough to cause serious crop damage.

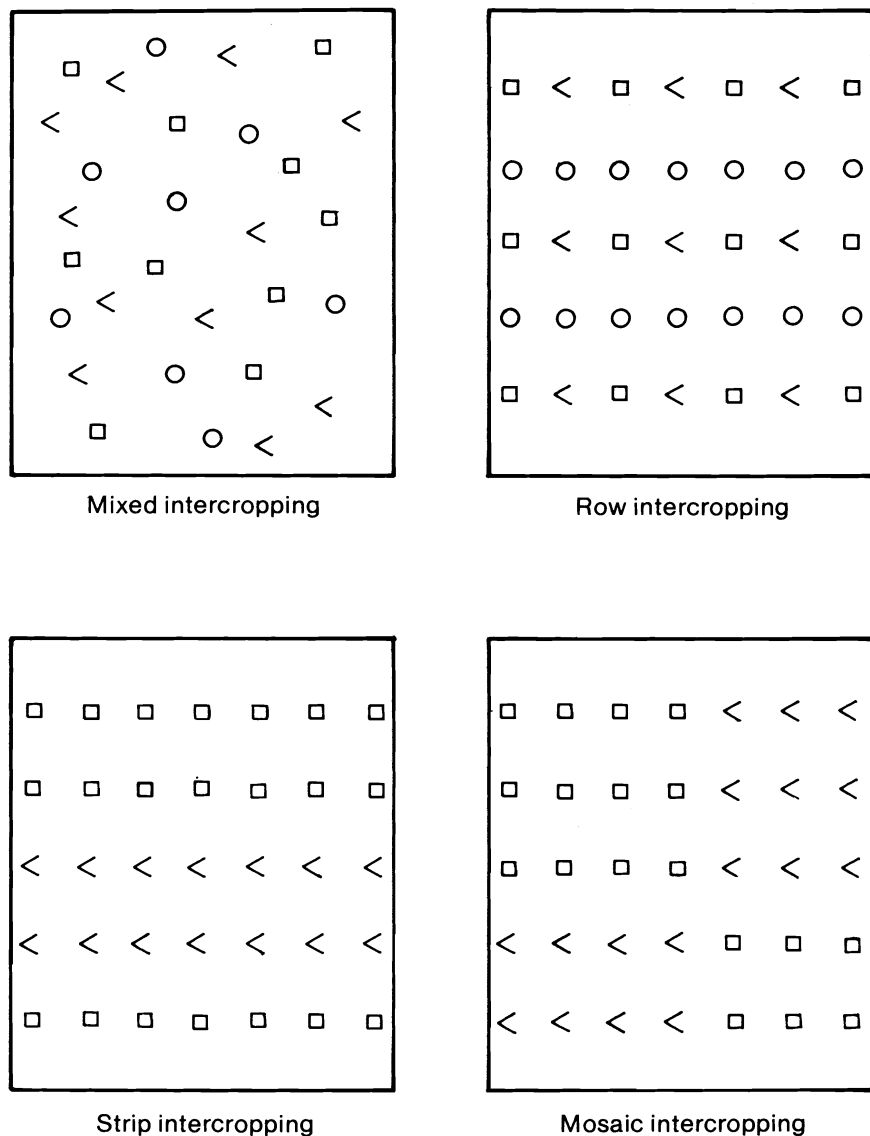
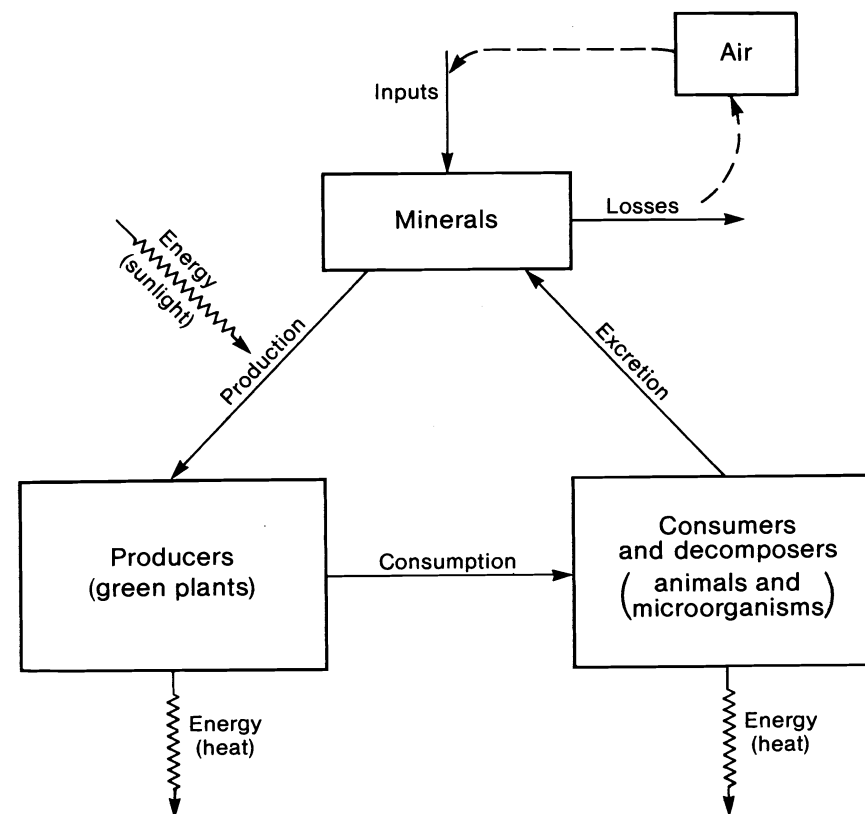
Traditional agroecosystems in Southeast Asia are notable for the complexity of their structure. Multiple cropping, the use of more than one kind of crop in the same field, is a common feature (Dalrymple 1971, Raheja 1973, Papendick et al. 1976, Kass 1978, Keswani and Ndruguru 1980, Beets 1982, Gomez and Gomez 1983). A single farm household may employ several cropping systems, each of which may include a number of crops, some of them interplanted in the same field at the same time. Interplanting trees with field crops (i.e., *agroforestry*) is not unusual in traditional agroecosystems. Figure 2.3 illustrates ways the different crops can be organized (i.e., mixed together) in space. They can be organized through time in the following ways:

- Sequential cropping—two or more crops that are cultivated one after the other. Double cropping is sequential cropping with two crops in a year, and triple cropping is three crops in a year. Ratoon cropping refers to the development of a new crop from the root system, stubble, or stems of the preceding crop instead of by sowing seed.
- Relay cropping—a sequence of two or more crops that overlap in time; a second crop is planted when the first crop reaches its reproductive stage of growth.
- Crop rotation—a cyclic pattern of two or more crops or mixed-cropping combinations on the same land in a regular and repeated sequence.
- Shifting agriculture—a form of crop rotation where one of the rotation stages is a fallow dominated by trees, bushes, or grass.
- Annual-perennial rotation—similar to shifting agriculture, except the “fallow” is intensively managed tree plantation.

The spatial ordering of the crops in a field gives an agroecosystem not only a horizontal structure but also a vertical structure because the leaves of different crops occur at different heights. For example, a field with sweet potatoes, corn, fruit trees (e.g., coffee or guava), and larger trees (e.g., *Albizia*) has four distinct leaf levels. The sweet potatoes provide a continuous cover of leaves at ground level, the corn may have a somewhat more discontinuous cover of leaves from one to two meters above ground, the fruit trees may be spaced out and have an even more discontinuous cover of leaves between three and five meters above ground, and the large trees might be scattered, with their leaves above five meters in height. In contrast, a garden next to a house might have a dense planting of fruit trees and taller trees, forming a nearly continuous canopy of leaves about three meters in height, so that crops close to the ground (like sweet potato) can survive only where there are gaps in the canopy allowing sunlight to pass through.

The vertical distribution of leaves in the field determines the pattern of photosynthesis by the crops and the total amount of agricultural production

Figure 2.3. Some Examples of Spatial Arrangements for Mixed Cropping

Figure 2.4. Production and Consumption in an Agroecosystem, Expressed in Terms of Mineral Cycling and Energy Flow<sup>a</sup>

<sup>a</sup> People are major consumers.

in the field. Because crops compete for the same sunlight, it is not possible to have the maximum production from each crop when taller and shorter ones are mixed in the same field at the same time. It is possible, however, for the total production from the mixture to be greater than it could be from any one of the crops alone.

#### ELEMENTS OF AGROECOSYSTEM FUNCTION

The numerous plants, animals, and microorganisms in all ecosystems, including agroecosystems, interact in a complex way. They display a diversity of biological activities, many of them associated with obtaining food and nutrition, which may be summarized as two major processes—production, also called primary production, and consumption (see Figure 2.4). Production

is the growth of green plants that results from photosynthesis. The carbon from carbon dioxide is joined into carbon chains that form the plants' living tissues (biomass). Consumption includes the metabolic activities of human beings, other animals, and microorganisms as they eat plants, animals, or microorganisms and use the carbon chains in their food for their own growth. In the process, many of the carbon chains are broken apart and released to the atmosphere as carbon dioxide.

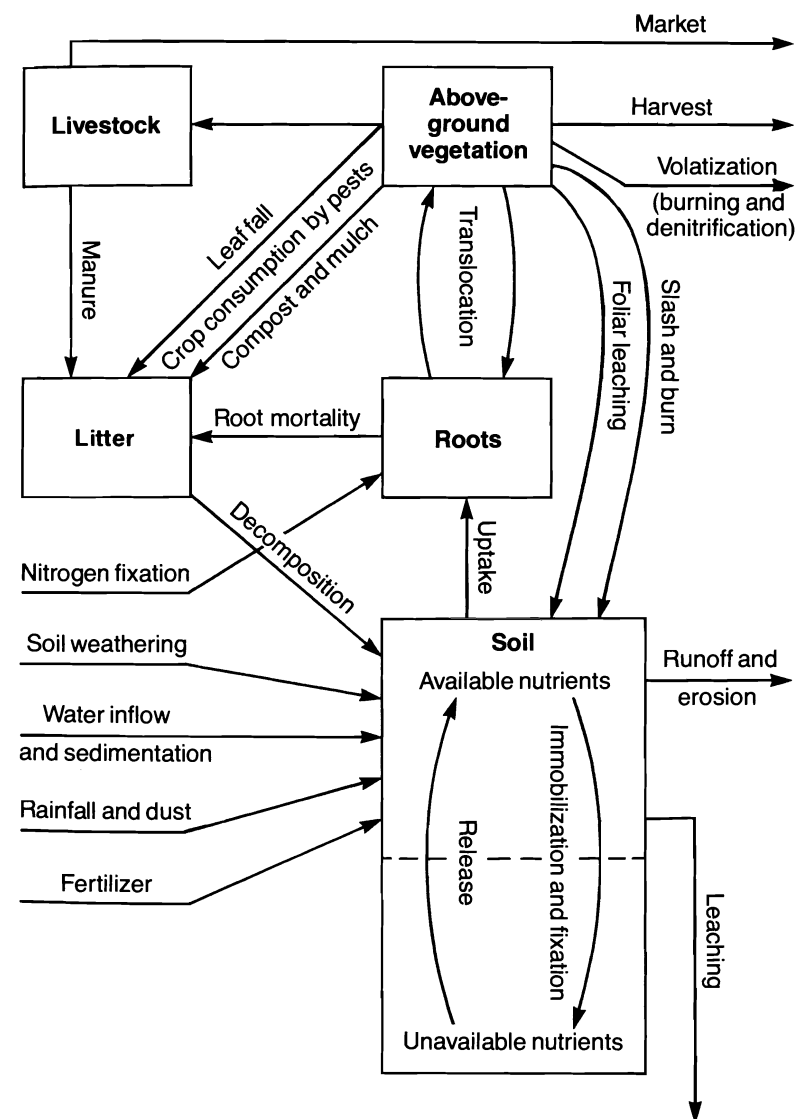
### Nutrient Cycling

In the course of production and consumption, mineral nutrients move through an agroecosystem in a cyclic manner (Figure 2.5). The most important elements are those required for photosynthesis (carbon, hydrogen, and oxygen) and for the construction of proteins and other structural and metabolic compounds (nitrogen, sulphur, phosphorus, calcium, magnesium). Potassium and some minor elements (iron, copper, boron, zinc, manganese) also are important for plant growth. Elements are transferred from the physical part of the ecosystem into the biological part of the cycle in the course of production. They are returned to the physical portion of the ecosystem whenever carbon chains are broken apart in the course of consumption. This returns nutrients to the soil where they can sustain plant production.

These mineral nutrient transfers take place through a variety of biological processes. Plants take up water and minerals through their roots, transpire (i.e., evaporate) water from their leaves, and incorporate the mineral nutrients into their tissues. Minerals then pass to the soil in plant litter (e.g., leaves and other plant residues) or animal waste and are released into the soil through decomposition. Plants take up carbon dioxide and release oxygen during photosynthesis, whereas the respiratory activity of both plants and animals leads to the consumption of oxygen and release of carbon dioxide. Some microorganisms consume nitrogen gas; others release it. As a consequence of these activities, there is a net exchange of gases such as carbon dioxide, oxygen, and nitrogen between the living and nonliving components of the ecosystem, between the soil and the air above the soil, and between an entire agroecosystem and the atmosphere above it.

Nutrients move through an agroecosystem not only in a gaseous form, but also on dirt particles and as ions (e.g., nitrate, phosphate, and sulfate) dissolved in water. Nutrients also enter the agroecosystem in dust and rainfall. As rainwater flows over leaves and branches, it carries minerals to the soil below. Nutrients also may enter the soil solution as they are dissolved out of tiny rock particles. Certain microorganisms bring atmospheric nitrogen into the system by converting it to ammonia, which can be used by plants. Other microorganisms transfer nitrogen out of the system by converting it back to the atmospheric form. Streams and underground water may flow into and out of the field, carrying nutrients with them, and as surface water percolates downward it carries (leaches) nutrients below the reach of crop roots. Nutrients are taken out of the soil solution (and

Figure 2.5. Movement of Mineral Nutrients In and Out of an Agroecosystem, As Well As Cyclically Between Soil and Vegetation (i.e., Crops and Weeds) Within the Agroecosystem



Source: Based on a diagram by Linda Christanty.

**Table 2.1. Estimated Inputs and Outputs of Nitrogen for a Traditional Southeast Asian Rice Paddy**

|                          | Kg/ha/yr |
|--------------------------|----------|
| <b>Inputs</b>            |          |
| Nitrogen fixation        | 64       |
| Atmospheric deposition   | 7        |
| Manure and crop residues | 27       |
| Total                    | 98       |
| <b>Outputs</b>           |          |
| Harvest                  | 51       |
| Leaching                 | 17       |
| Ammonia volatilization   | 2        |
| Denitrification          | 18       |
| Erosion                  | 5        |
| Grazing                  | 7        |
| Total                    | 100      |

Source: Wetselar et al. (1981).

therefore made unavailable to plants) when they are incorporated into the bodies of microorganisms (immobilization) or when they combine chemically with other substances in the soil (fixation).

Farmers move nutrients in and out of the agroecosystem when they bring in chemical or organic fertilizers (e.g., manure or compost) or remove the harvest or any other plant materials from the field. Table 2.1 illustrates the movement of nitrogen in and out of a traditional Southeast Asian rice field, and Chapter 10 describes the cycling of mineral nutrients in a number of Southeast Asian agricultural systems.

### Energy Flow

Energy enters an agroecosystem as sunlight and undergoes numerous physical transformations. Soil and plant surfaces absorb sunlight and emit infrared radiation, and warm air carries heat energy as it passes to areas of cooler air. Heat passes from the soil to the air above and from the farm field to the atmosphere above during the day and in the opposite direction at night.

Biological energy flow refers to the transfer of energy into plants by photosynthesis (production) and from one organism to another through the food web (consumption). The movement of energy is not cyclic like the movement of nutrients. Energy is incorporated into living tissues when sunlight energy is bound into the carbon chains that green plants use for their production (i.e., growth). The carbon chains contain potential energy that plants can use to live and grow. Internal consumption of energy for metabolic purposes is respiration, and some of this energy is lost as heat.

The net energy that goes into the growth of the plant after respiration (i.e., its net accumulation of potential energy in carbon chains) is net primary production.

Animals and microorganisms are consumers that have a variety of ecological roles (e.g., herbivore, fructivore, predator, parasite, pathogen, scavenger, decomposer), depending upon the kind of food they eat, whether it is alive or dead, and whether or not they eat it whole. Human beings are major consumers in agricultural ecosystems, but many other consumers also have major roles in agroecosystem functioning. Consumers that feed upon plants use the carbon chains in their food as building blocks to construct their own tissues; they break down a certain percentage of the chains in order to release energy for their metabolic needs (i.e., respiration). Nutrients that are acquired in surplus of the animals' needs are excreted to the environment (e.g., nitrogen is excreted as ammonia or urea), and the rest of the energy and minerals is retained for their growth. The plants tend to limit the animals that feed upon them by being inedible, indigestible, or toxic, but animals that specialize in feeding on a particular kind of plant may have evolved metabolic or behavioral means of overcoming the plant's defenses. Some animal consumers may compete with people and be regarded as pests.

Consumers that feed on other consumers use the energy and nutrients in their food in a similar way. As one consumer eats another, there is a flow of biological energy along a food chain, and there is a loss of energy (in respiration) at each step. The percentage of energy at one step that is consumed by the succeeding step is the food chain efficiency, typically 10–50 percent. Energy that is not passed to the next step in the chain is lost as heat. In an agroecosystem the number of steps in the food chains that lead to human beings and the efficiency of each step in the chain determine the overall efficiency with which the primary productivity is channeled to people.

Sunlight is the only major source of energy input in most natural ecosystems, but human energy inputs are significant in agricultural ecosystems. They include human and animal labor, mechanized energy inputs (e.g., plowing with a tractor), and the energy content of introduced chemicals (e.g., manures, fertilizers, and pesticides). Human energy inputs in an agroecosystem do not feed directly into the biological energy flow as sunlight does. Human energy inputs are used to shape agroecosystem structure, thereby shaping energy flow through effects on primary production and the percent of that production that is channelled to products for human use (Norman 1978, Bialy 1982, Schahczenski 1984).

### Productivity, Stability, and Sustainability

In addition to the numerous ecological processes that can be viewed in nutrient cycling and energy flow, there are three significant properties of an agroecosystem that reflect how well it is functioning. These are *productivity*, the yield of goods and services from an agroecosystem; *stability*, the reliability or constancy of the yield; and *sustainability*, the viability of the agroecosystem,

or its capacity to continue producing on a long-term basis (Conway 1985). These three characteristics are consequences of complex ecological processes within the agroecosystem as well as interactions of the agroecosystem with the outer world, including the human social system and other agroecosystems.

The productivity of an agricultural system usually is evaluated by tonnage yield of agricultural products or the monetary value of those products. Productivity can also be interpreted more broadly, however, to include products such as human nutrients (e.g., calories, vitamins, minerals, and amino acids), medicines, building materials, soil conservation, watershed functions, esthetic functions, and provision of a favorable environment for social interaction.

Stability is important because people depend upon a certain level of production year after year. Nonetheless, agricultural production often fluctuates from year to year, particularly on marginal land where periodic fluctuations in rainfall, pests, and a variety of other natural phenomena may increase or decrease yields. Although risks of partial or complete crop failure are an unavoidable part of farming, subsistence farmers in the tropics place a particularly high priority on minimizing those risks. Local crop varieties can be important to these farmers, because the local varieties are often resistant to pests, drought, soil nutrient deficiencies, and other environmental stresses of the area. By having a collection of different seed types on hand, farmers can choose varieties appropriate for a planting season's unique characteristics. Small-scale farmers also feel secure when they can employ cropping systems based on a technology they understand well, knowing they can provide the necessary inputs and knowing they can use or sell the resulting products.

During short-term stresses, traditional farmers are usually well prepared to make the short-term adjustments necessary to reinforce the stability of the household farm system. For example, a number of strategies are used to reduce risks due to drought (Jodha and Mascarenhas 1983). A common feature of those strategies is a diversity of complementary crops, including perennials that are drought resistant and livestock that can use marginal lands in times of drought. A dependence on outside resources is reduced to a minimum in traditional farming, with assets and products from good times stored for sale or consumption during difficult times. Adjustments during difficult times include a reduction in consumption, fuller use of low-value agricultural products and products from nature (including less palatable foods), more intensive care of crops, postponement of cash outlays, sale of assets (e.g., trees, livestock, or stored crop products), and an increase in off-farm labor (see Table 2.2).

Sustainability in an agroecosystem is a problem when human activities cause ecological changes that will undermine the continuing productivity of the ecosystem. Perhaps the most common sustainability problems are associated with undesirable changes in the soil, but weeds, diseases, and animal pests also can build up to a point where crops no longer function as the farmer needs. Sustainability may also be in jeopardy if the agricultural

**Table 2.2. Loss Minimizing Activities During a Drought Year and Nondrought Year in an Indian Village**

| Loss Minimizing Measure                                   | Percentage Taking Measure |                          |
|---|---------------------------|--------------------------|
|   | Drought Year<br>(1964–65) | Normal Year<br>(1963–64) |
| <b>On plots</b>   |                           |                          |
| Collected weeded material as fodder                       | 32                        | 3                        |
| Harvested field borders for fodder                        | 40                        | 4                        |
| Harvested crops prematurely                               | 16                        | 0                        |
| Harvested crops by-product only                           | 29                        | 1                        |
| Harvested mature crops                                    | 10                        | 86                       |
| Intercropping   | 4                         | 39                       |
| Weeded more than once                                     | 11                        | 0                        |
| Thinned crops   | 22                        | 0                        |
| Postsowing operations omitted                             | 21                        | 0                        |
| Hired resources used for postsowing operations            | 1                         | 14                       |
| Harvested premature <i>z. numularia</i> (bush) for fodder | 55                        | 0                        |
| Lopped trees for fodder or fuel                           | 32                        | 2                        |
| <b>In households</b>                                      |                           |                          |
| Nonpayment of dues  | 35                        | 3                        |
| Marriages postponed                                       | 6                         | 0                        |
| Children withdrawn from school                            | 24                        | 2                        |

Source: Jodha and Mascaranhas (1983).

Note: The drought year had 159 mm total rainfall and eight rainy days. The normal year had 377 mm total rainfall and twenty rainy days.

system lacks *resilience* (Holling 1978)—the ability to withstand severe and unexpected perturbations such as a prolonged drought, the introduction of a new agricultural pest or disease, a significant change in markets, or an increase in the cost of inputs. The sustainability and resilience of an agricultural system are decreased when it is dependent on inputs that may not be available at some time in the future. Self-sufficiency can increase sustainability. A strategy of subsistence farm families is to aim for resilience in the total farm system such that if one component should fail there will be others to fall back on.

Although it is desirable for an agricultural system to be high in all three qualities—productivity, stability, and sustainability—the three are often in conflict with one another. Highly productive agricultural systems often entail high risks that reduce their stability. For example, highly productive crop



varieties may fail if nutrient inputs, water supplies, or protection from pests are not adequate; planting a large area to a single best crop variety can make an area particularly susceptible to a major pest outbreak. Highly productive systems also may place a drain on ecosystem resources, jeopardizing the continued sustainability of the system. For example, highly productive crops may remove large quantities of mineral nutrients from the soil, nutrients that consequently leave the field when the crops are harvested instead of remaining in the field to be recycled for further crop production. Finally, stable agriculture may not be resilient to unexpected disturbances because the capacity for dealing with such disturbances is not used. For example, establishment of an irrigation system can lead to more stable production for crops and agricultural practices that depend on the steady water supply. However, this may eventually lead to a loss of knowledge of the practices of rainfed agriculture that could be necessary if the irrigation system should fail.

## TRADITIONAL AGROECOSYSTEMS AND NATURAL ECOSYSTEMS

### *Natural Ecosystem Design*

Every ecosystem can be said to have a design that is responsible for how it functions. Natural ecosystems such as tropical rainforests are the product of a long process of natural selection that has generated a highly intricate organization at the level of the ecosystem as a whole (Marten 1985). The design of a natural ecosystem serves one function above all—the continued functioning of the ecosystem, its persistence. The sustainability of natural ecosystems is extremely high.

Natural ecosystems derive their whole-system behavior and, most important, their persistence from the fact that the living components fit together. A natural ecosystem is not a random collection of plants, animals, and microorganisms. All the species are highly adapted to the physical environment and also highly coadapted to one another. The plants and microorganisms are adapted to growing under the ecosystem's soil and moisture conditions and preventing themselves from being totally consumed by animals that feed upon them. The animals are adapted to locating the particular organisms on which they feed and avoiding their natural enemies. If a randomly selected organism is introduced to an undisturbed tropical rainforest, chances are it will not survive because it does not fit.

A natural ecosystem derives its whole-system behavior from the fact that the actions of each component are constrained by the actions of other components. Although all the numerous plants, animals, and microorganisms in an ecosystem have the reproductive capacity to multiply to enormous numbers, their populations are in fact held in check by natural enemies, limitations in the resources they require for growth, and other negative feedbacks in the ecosystem. This containment of each part by the other

parts prevents any one part from unduly disrupting, or even destroying, the system as a whole.

Another important property of natural ecosystems is redundancy, the duplication of function. There is considerable overlap of function between the different organisms in a natural ecosystem, and ecosystems with a high level of redundancy have a greater persistence. If a single species is removed from a tropical rainforest, the forest may continue to function almost as though nothing had happened.

Finally, natural ecosystems are adaptive. They are able to persist in the face of external disturbances because they change in response to changing conditions. An example is *succession*, an orderly progression in the species composition and structure of an ecosystem (i.e., a change in plant and animal communities). If a portion of a forest is destroyed by fire, or if a patch of forest is opened by a fallen tree, the opening is occupied by a different group of plants and animals than those in the original forest. The new plants and animals are better adapted to the environmental conditions created by the opening, but over the years their presence causes environmental changes (e.g., soil changes and shading) so they are replaced by other plants and animals more suited to the new conditions they have created. The process eventually leads to the same forest as before (Figure 2.6).

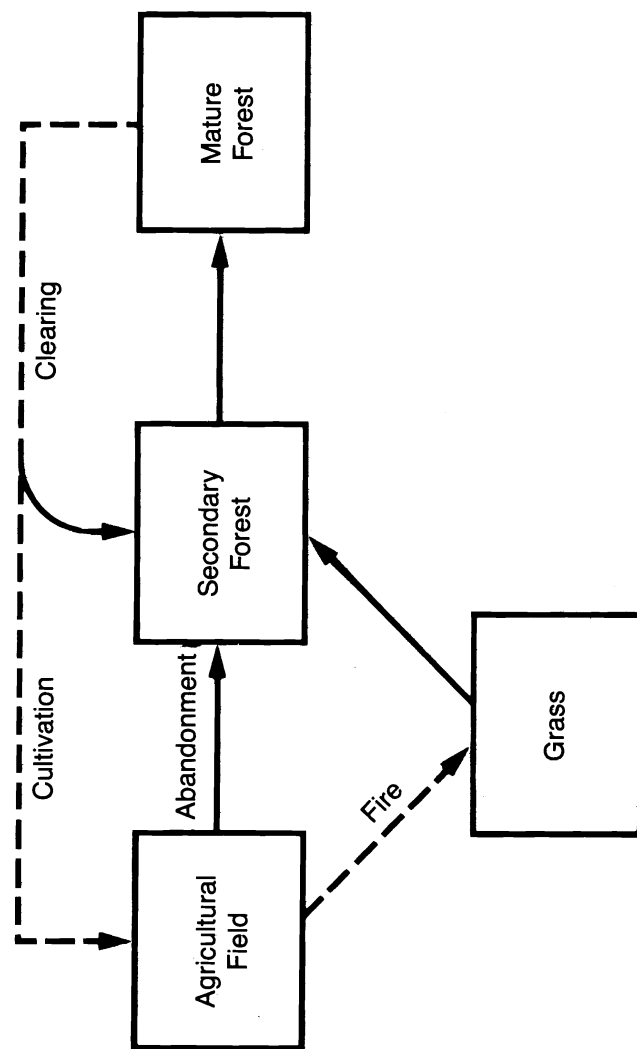
As a consequence, natural ecosystems are organized not only in time, but also in space in a way that helps them to continue functioning despite environmental disturbances. At any one moment an area may have a patchwork of communities in various successional stages. The mature forest and the successional stages leading up to it constitute a total system adapted to the fluctuating environmental conditions of the area. Just as a diversity of species in the total ecosystem is essential for succession to proceed, diversity is the key to many other aspects of ecosystem adaptability.

### *Traditional Agroecosystem Design*

Agroecosystems differ from natural ecosystems because people perform a significant role in shaping agroecosystems, with the explicit purpose of providing products for human use. Whereas the living components of a natural ecosystem are a product of millennia of biological evolution adapting them to the physical environment and to one another, the major components of agroecosystems (i.e., crops and livestock) have been selected by humans over a relatively short time. In recent years, some agroecosystem components (e.g., "high yielding" varieties) have been selected by a very rapid process of scientific breeding that leads to highly specialized characteristics such as responsiveness to fertilizers or increasing the fraction of the crop biomass that is useful. Characteristics such as resistance to pests, drought, and lodging may not be linked genetically to crop yields and may therefore be sacrificed in the process.

Compared with forests and most other natural ecosystems, most agroecosystem designs are less complex and intricate. The coadaptation of components is less complete, there is less redundancy, and most agroeco-



Figure 2.6. Stages of Community Succession in a Tropical Landscape<sup>a</sup>

<sup>a</sup> Solid arrows indicate natural changes; dashed arrows indicate changes induced by people.

systems are therefore less equipped to persist on their own. An agricultural ecosystem such as a sugarcane field, a rice paddy, or a pasture may be more productive than the natural rainforest that once occupied the same land, and it will certainly channel a much greater percentage of its production to human consumption than the forest did, but it is not self-sustaining and may be relatively vulnerable to external disturbances. The soil may be too infertile for continuous crop growth unless it is fortified with fertilizers, or pests may destroy the crops unless they are held in check by pesticides.

Because traditional agroecosystems are often a product of centuries of cultural and biological evolution, the degree of coadaptation of their components, the adaptation of the system as a whole to the surrounding physical environment, and their productivity, stability, and sustainability are often more similar to natural ecosystems than is modern agriculture. Traditional agriculturalists often have manipulated existing natural ecosystems so the structure and function of the components remain the same but useful species replace their natural analogues, an approach that carries with it many of the advantages and disadvantages of natural ecosystems.

An advantage to mimicking natural ecosystems is that there is less dependence on inputs such as mineral nutrients from outside the system. A tropical rainforest on poor, nutrient-depleted soils has a variety of intricate mechanisms for holding mineral nutrients within the system. Its main strategy is to hold nearly all the nutrients in the living organisms themselves, so only a small fraction of the minerals are in the soil where they have the possibility of being washed out of the system. In addition, when leaves fall to the forest floor, they may be decomposed by special fungi that pass minerals such as phosphorus from the leaves to plant roots without ever releasing minerals into the soil solution (Jordan and Stark 1978).

Because an agroecosystem on poor soil cannot afford to lose excessive mineral nutrients through leaching or removal in the harvest, traditional agroforestry, a combination of field crops and tree crops on the same land, often mimics a natural forest to maintain mineral nutrients within the system. Tree crops have deep root systems that can capture nutrients that have leached deep in the soil below the reach of field-crop roots and deposit the nutrients on the soil surface when they shed their leaves. Some trees in traditional agroforestry fix nitrogen (Roskoski 1982). The use of inputs in agroforestry is qualitatively and quantitatively different from their use in modern, large-scale, commercial monocultures. Fertilizers in traditional agroforestry are not a massive supplement to achieve high yields and compensate for high nutrient leaching rates; they are a replacement of minerals lost through export in a system with tight mineral cycles (Dickenson 1972).

A continuous vegetative cover is an attribute of natural ecosystems that traditional agroecosystems often mimic to help ensure their sustainability. For example, the closed canopy and minimal soil disturbance provided by the diversity of crops in a traditional agroforestry field help to maintain soil fertility and reinforce the retention of mineral nutrients within the system. Erosion in a forest can be as little as one-hundredth the erosion

of a typical field crop because the vegetative cover in a forest protects the soil. The closer agricultural systems come to having a complete and continuous cover like that in natural ecosystems, the less the risk of erosion. Vegetative cover also provides leaf litter that adds to the soil organic matter. Both cover and litter shade the soil and protect it from the high temperatures that can lead to excessively high levels of bacterial metabolic activity that deplete soil organic matter and nitrogen, degrade soil structure, and reduce soil moisture and nutrient storage capacities.

When a humid tropical forest is replaced by an agroecosystem (e.g., a maize field) that does not mimic the natural vegetative cover, increased fertilizer inputs may be required to compensate for soil degradation. The correction of one problem, however, can lead to other problems that threaten the persistence of a poorly adapted agroecosystem. For example, compensating for a loss of soil nitrogen by applying sulfate of ammonia, the standard nitrogenous fertilizer in much of the tropics, may acidify the soil, leading to a deficiency in available phosphorus due to fixation by iron oxides or placing other stresses on crops that cannot tolerate acid soils (Janzen 1973).

Succession (Figure 2.6) is another feature of natural ecosystems that can be mimicked by traditional agroecosystems. When agricultural ecosystems are maintained as artificial ecosystems very different from the natural ecosystems they have replaced, problems may occur because of successional changes toward the natural ecosystem of the area. For example, cropping may induce changes in the soil that make an agricultural field more suitable for weeds than for crops. Farmers often plow to destroy weeds and disrupt the succession that interferes with their agricultural ecosystem, but many traditional agriculturalists use a forest fallow as a successional process to deal with the same problem. They prepare for the fallow with explicit cultivation practices such as maintaining forest vegetation in the vicinity of their fields as a source of seeds to facilitate establishment of the forest when they put their land into fallow.

A forest fallow serves many functions, one being to rebuild soil that has degraded under agricultural use. During the fallow, trees draw mineral nutrients from deep in the soil and use those minerals for the growth of their leaves. When the leaves fall to the forest floor, they replenish nutrients in the topsoil as they decompose. A forest fallow also serves to control weeds. For example, slash-and-burn fields are often invaded by weeds, the first stage in a natural succession that occurs whenever a patch of forest is opened. Without a fallow it may only be possible to combat weeds with external inputs such as herbicides, which are not only costly but may have undesirable side effects on the environment. Allowing the succession to take place instead of preventing it, i.e., allowing a fallow that eventually leads to replacement of the field by a weedless, mature forest, is working with nature's strategy instead of struggling against it.

#### THE SPECIAL ROLE OF MIXED CROPPING

The fact that small-scale farmers in the tropics often grow many different kinds of crops rather than specializing in a few is a key part of their

subsistence strategy. A diversity of crops provides a balanced diet, serves a variety of household needs, and spreads labor requirements and the harvest over the year, reducing the amount of food storage required. Mixed cropping (i.e., interplanting a number of crops in the same field) deserves special consideration in any discussion of traditional agriculture because it is so common, particularly in homegardens and upland areas. It also can have far-reaching effects on how agroecosystems function, and on the quantity and reliability of production, particularly under marginal environmental conditions. The effectiveness of mixed cropping depends largely on competition for light, water, and mineral nutrients among individuals of the same crop and of different crops. In theory, a mixture of crops could perform better or worse than a single-crop monoculture, depending upon the mixture, but the noteworthy feature of traditional mixed cropping is that it generally performs better than a monoculture (Wilken 1977, Jodha 1980, 1981).

#### Productivity

The productivity in mixed cropping experiments has been measured by the Land Equivalent Ratio (LER) (Willey 1979a):

$$LER = \sum_i \left( \frac{x_i}{y_i} \right),$$

where

$x_i$  = the yield of each crop in a mixture and  
 $y_i$  = the yield of the same crop in a pure stand.

If the LER is greater than 1, the mixture has a higher productivity than component monocultures. Numerous researchers (IRRI 1974, Baker and Norman 1975, Francis et al. 1976, Sastrawinata 1976, and Crookston 1976; also see review by Kass 1978) have used this measure since it was introduced by Niqueux (1959) for evaluating groundnut-maize and groundnut-sorghum mixtures in Chad. An LER of 1.6 (Baker and Norman 1975) is a typical value for mixed cropping in farmers' fields in Nigeria. LERs of up to 2.0 have been reported (Andrews and Kassam 1976).

Trenbath (1974) found the following distribution of LERs in a survey of 572 experimental mixtures:

| LERs    | Percentage |
|---------|------------|
| 0.5-0.9 | 13.6       |
| 0.9-1.1 | 66.1       |
| 1.1-1.7 | 20.3       |

Although experimental mixtures seem to have slightly higher yields than monocultures on average, the difference is not very great. It is therefore the particular combination of crops, rather than a mixture per se, that may

be responsible for higher yields. Mechanisms that seem to be responsible for this include:

- More efficient exploitation of soil, water, and energy resources;
- Greater resistance to crop damage; and
- Stimulation of crop growth by biochemical interactions between interplanted crops of different species.

Plants compete for light, water, and soil nutrients at a given place and time. A significant feature of these resources is that they vary from one place to another and from one time of day, month, or season to another, and intercropping produces higher yields than monoculture to the extent it is able to use the resources more fully over this variation. Any differential in the environment can give an advantage when matched with a corresponding differential in crop characteristics. Intercropping can provide superior temporal exploitation. Among cereals, for example, the greater the difference between crops in days to maturity, the greater is the gain due to mixing them (Baker and Norman 1975). The resulting yield advantage can be as great as 20–80 percent (Willey 1979a), the most significant gains occurring when there is a difference of at least five weeks between the time of maturity for cereals (Baker and Norman 1975). Temporal separation does not always increase yields, however; May (1980) found the LER of a gram-millet mixture to be insensitive to different planting schedules.

Intercropping also can provide superior spatial exploitation when light is captured by the vertical stratification of a mixed crop canopy or when water and nutrient uptake is increased by the root zonation of a crop mixture (Trenbath 1981). A commonly used measure of light interception is the Leaf Area Index (LAI) defined as the area of leaf (one side only) per unit area of ground (Black 1958). A crop in a mixture is at a competitive advantage if its leaves are highest in the canopy, and plants with horizontal leaves intercept more light than those with erect leaves. From theoretical and experimental results it appears that optimal canopy configurations (e.g., erect leaves over prostrate leaves, allowing a substantial percentage of light to reach crops that are lower in the canopy) may be sufficient to explain the higher yields in many crop mixtures. The potential benefits from superior light interception are often limited, however, by water and nutrients where traditional agriculture is practiced (Snaydon and Harris 1981, Willey 1979a). The ways in which intercropping can increase the uptake of soil water and soil nutrients are described in detail in Chapter 10.

Weed control is another reason for higher yields from mixed cropping. Crops such as maize, millet, sorghum, and rice do not develop enough foliage to control weeds effectively by shading them out, and even crops that eventually develop enough foliage to suppress weeds may need a companion crop to aid weed control when first planted. For example, cucurbits are grown with maize in the Ubangi area in Africa because they choke out weeds and help conserve moisture (Miracle 1967).

### Stability

Intercropping has greater yield stability than monoculture; that is, the harvest is more reliable and less variable from year to year (Kass 1978). This is largely because intercropping is less sensitive to environmental variation than monoculture (Trenbath 1974). Quantitative evidence for the greater stability of intercropping has come largely from measurements of the variation in yields under different growing conditions. For example, over a period of three years the yields from oat-barley mixtures varied less than those from pure stands of oats or barley (Morrish 1934). Yields of oat-pea mixtures varied less over different years and different locations, as well as among different fields at the same location, than pure stands of oats or peas (Gliemeroth 1950). Further evidence of this kind is reviewed by Trenbath (1974) and Willey (1979b).

Crop compensation is a major basis for the stability of intercropping. Climatic conditions vary from year to year and at different times during the same cropping season; soil conditions vary from location to location and even from spot to spot within a single field. Different growth requirements of component crops in mixed cropping systems make it likely that at least one of the crops will produce even if environmental conditions damage the other crops, and there should be something to harvest even in the worst season. The importance of crop compensation is widely supported in theory (Marshall and Brown 1973, Trenbath 1974, Andrews and Kassam 1976) and in empirical studies of traditional agricultural systems (Ogunfowora and Norman 1973, Igbozurike 1978, Jodha 1980, Raheja 1973). A maize-bean mixture had a greater advantage over sole cropping ( $LER = 1.87$ ) in fields where the maize suffered from hail damage and disease compared with fields where the problem did not occur ( $LER = 1.08$  and  $1.24$ ) (Fisher 1976).

The same principle applies to mixtures of different varieties of the same crop species. Because different genotypes perform differently under different microenvironmental conditions, a mixture of varieties has greater production stability than a pure line. This was demonstrated for lima beans (Allard 1961), where the variation in yields from different locations and years was about 50 percent greater for a homogeneous planting of a pure line than it was for a mixture of varieties. The same pattern should be true of the numerous crops for which traditional farmers often employ dozens of varieties within a single village (Rerkasem and Rerkasem 1985).

The characteristics that add reliability to intercropping systems are similar to those that increase productivity: weed exclusion (Bantilan et al. 1974), greater resistance to insects and diseases, increased drought tolerance resulting from root stratification, increased microclimatic humidity due to shading and windbreak effects in multistoried systems (Baldy 1963), increased flooding and frost tolerance, and decreased lodging where lodging in a mixture generally follows the behavior of the more resistant component (Trenbath 1974). The stability of mixed cropping may have economic considerations as well as agronomic ones, as evidenced by reports that multiple cropping offers more dependable returns on investments of labor and capital than

does sole cropping (Evans 1960, Ruthenberg 1980, Andrews and Kassam 1976). Flexibility in the timing of planting and harvesting allows synchronization with weather conditions because a farmer with a large number of local species and varieties at his disposal can select those appropriate for each year's rainfall regime. Flexibility in the timing of the harvest also provides a return from early maturing varieties if there is insect damage to the later crops. Flexibility in harvest also avoids labor bottlenecks that lead to crop losses, since the peak labor demand is spread over a longer period and away from some critical point (Norman 1974).

### *Sustainability*

The major impact of mixed cropping on agroecosystem sustainability is its effect on soil quality. The total crop production from intercropping can be greater than from monocropping, including not only parts of the crop that are removed in the harvest but also those parts that remain on the field as crop residues. Crop residues form litter that protects the soil from the impact of the raindrops that have a key role in soil erosion, and the residues sustain soil fertility by adding organic matter to soil. Mixed cropping also provides the opportunity to maintain crops on the field throughout a greater percentage of the year, thereby increasing the likelihood that there will be a protective crop cover to help minimize erosion when heavy storms occur. The role of traditional mixed cropping in preventing soil erosion and maintaining soil fertility is discussed further in Chapter 10.

## **SOCIAL SYSTEM IMPACTS ON AGROECOSYSTEMS**

### *Agricultural Technology*

Farmers structure their agroecosystems by way of the technology they apply. The technology can be described to a large extent in terms of cropping systems—the particular crops (or livestock) that are employed and how they are organized in space and time. A distinguishing characteristic of the technology of small-scale farmers in the tropics is that much of it is a product of centuries of trial-and-error evolution that has adapted it to local environmental and social conditions. Although a major part of traditional agricultural technology may have its roots in the distant past, it is not static. Traditional agricultural technology has always changed in response to changing needs, and it continues to change today. In fact, the technology of many small-scale tropical farmers today is a mixture of indigenous, traditional technology and the modern agricultural technology introduced in recent years from North America and Europe.

Traditional knowledge is an important part of traditional technology (Brokensha et al. 1980), and it can be highly intricate. It provides the basis for day-to-day decisions on which crops to use and what cultivation practices to employ as agricultural fields or gardens proceed through their cropping cycles, a scenario that can be very different as the weather changes from

year to year. It is also an essential part of a farmer's knowledge to be able to detect subtle differences in soil quality and to know what crops can succeed in particular kinds of soil. Traditional knowledge extends to all ways that farmers perceive and conceptualize the structure and function of their agroecosystems.

### *Farmer Decision Making*

The structuring of agroecosystems takes place through decisions that farmers make in selecting the technology they apply (Figure 2.7), a topic that is discussed at greater length in Chapter 7. These decisions depend not only upon the technology that is available and the natural resources with which the farmer has to work in shaping his agroecosystem, but also upon diverse sources of information and numerous aspects of the human social system that interact with one another and with the technology in shaping farming decisions (Bartlett 1980). An agroecosystem structure that is appropriate for one set of environmental and social conditions may be completely inappropriate for other conditions.

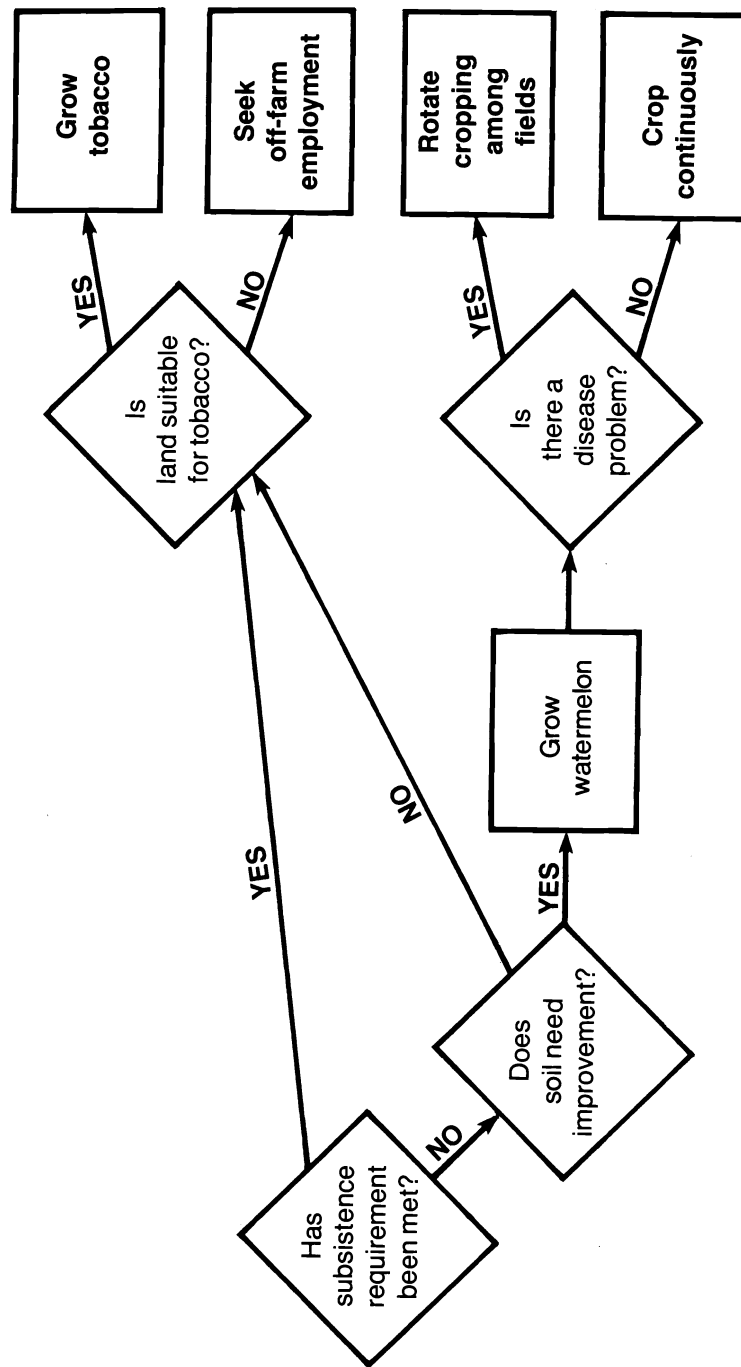
The mix of different kinds of land that a small-scale farm household has for agricultural use is a major consideration in deciding what to plant, where, and when. A household may have a small amount of land around the house that is most convenient to tend carefully. It may have some lower paddy land that is assured of sufficient water for rice during the rainy season but also may be flooded during a wet year. It also may have some upper paddy land that has no risk of flooding but is not sure to have sufficient water for wet rice during a dry year. Finally, it may have some upland fields, which depend entirely upon rainfall and are suited only for crops other than rice. A household with all these different kinds of land can balance its crops to meet a variety of family needs and balance its risks at the same time. A household with only one or two kinds of land has to adjust its uses accordingly. For example, a household with no paddy land may emphasize more starchy crops in its upland fields than it otherwise would in order to compensate for the fact that it is not able to produce rice in paddies, or it may grow cash crops and purchase rice with the money.

The annual rainfall schedule is also important. Although there may be more than enough rainfall during the tropical rainy season, water supplies may be equally deficient during the dry season. The skill of the farmer is directed toward employing crops that can make full use of the water when there is an ample supply complemented by crops that can make use of residual soil moisture during the dry season. Traditional agriculture often features options especially intended for unfavorable conditions. For example, cassava may be cultivated as a less desirable food to fall back on, and homegarden trees can be a form of savings that a household can sell when an exceptional need for cash arises.

The human social system conditions agricultural decisions in many ways. A social system can be viewed most simply in terms of technology, population,



Figure 2.8. Simplified Scheme for Farmer Cropping Decisions on a Field Crop After Rice in Northeast Thailand



Source: Based on Limpinuntana et al. 1982.

### AGROECOSYSTEM IMPACTS ON SOCIAL SYSTEMS

The constant process of coadaptation between agroecosystems and human social systems leads to agroecosystem function stimulating adjustments in the social system that in turn are aimed at successful agroecosystem function. Values, customs, religion, and rituals codify traditional agricultural technology and ensure that farmers put the technology effectively into practice, a process illustrated in considerable detail in Chapter 3.

A drastic change in the agricultural system can induce correspondingly drastic changes in the social system. For example, the introduction of new, nonphotoperiod-sensitive rice varieties to Northern Thailand has provided the opportunity to grow rice outside of the traditional growing season. It is now possible to intensify production from traditional double cropping (traditional rice followed by a field crop) to triple cropping (traditional rice followed by the new rice variety followed by a field crop). But triple cropping makes extremely heavy demands on labor, and people no longer have as much time for traditional religious festivals and are too busy for traditional cooperative labor exchange, social activities that served useful functions in the past (Ramitanondh 1985). Although their total income from triple cropping is higher than from double cropping, the return on their capital and labor investment from the third crop is relatively low because it is cultivated at a time of year when weather is marginal. Finally, triple cropping has led to a relative increase in wealth by the village elite and has created a dependence of all on inputs (e.g., chemical fertilizers) that come from the outside world.

The most important impacts of agroecosystems on human social systems derive directly from the intended agroecosystem outputs—the nutritional, monetary, energetic, and other values of agroecosystem products—but there also can be significant impacts from unintended “products.” For example, agroecosystems can have a significant effect on human health not only by way of nutrition but also by way of communicable diseases. Some tropical agroecosystems are habitats for disease vectors such as *Anopheles* mosquitoes that carry malaria and snails that act as alternate hosts for liver flukes and bilharzia. The fact that the way crops are structured in space and time determines the kinds of habitats that agroecosystems provide for disease vectors has probably been a significant factor in the evolution of traditional agroecosystems over the centuries.

Agroecosystem function can have a profound impact on the human population itself, directly by way of the physiological impact of nutrition on fertility and mortality, and indirectly by way of social behavior. If land is in short supply for agricultural production, land tenure arrangements can be particularly elaborate, and some members of a farm family may seek off-farm employment or migrate to the city, placing constraints on the labor available for agriculture and placing limits on which agricultural systems are feasible. If land is abundant and labor is limited, children may take on a value as a source of labor, leading to large families and a high rate of

population growth. On the other hand, if agricultural production is seriously low compared with the needs of the population, young people may delay marriage, taking measures to avoid the responsibility of children, people may adjust their diets to less-favored foods, or they may minimize activity so as not to consume unnecessary calories.

#### IMPACT OF AGROECOSYSTEM FUNCTION ON THE NATURAL RESOURCE BASE

Agroecosystem function can change the natural resource base, an impact with significant consequences for agricultural sustainability. Perhaps the most important impact is soil conservation—maintaining soil fertility and preventing soil loss due to erosion. Protecting the soil from erosion is primarily a function of the timing of cover provided by soil litter, crops, and other vegetation (including weeds) in the agroecosystem and how the cover is aligned with the timing of heavy rainstorms. Most of the erosion on a field can be caused by the few heaviest rainstorms in the year if the soil surface is bare. Tree leaves, crop residues, and other forms of mulch reduce erosion not only through the cover they provide, but also by increasing the organic matter content of the topsoil, making the soil more permeable to water and reducing water runoff that can carry soil particles away. Crop cover also affects the functioning of an agroecosystem as a watershed. Excessive runoff can lead to flooding of agroecosystems downhill in the watershed and possibly reduce the supply of stream water for those agroecosystems during the dry season. Agroecosystems that depend upon underground water (through wells) establish an equilibrium with underground water supplies that determines whether the agroecosystems are viable. The organization of water supply can be a major function of village social organization (e.g., irrigation societies). An agricultural system that progressively undermines its resource base cannot be sustainable. Knowing how traditional agriculture affects the land, water, and other resources on which it depends is the key to understanding why it has been able to function for centuries on a sustainable basis.

The human carrying capacity of an area (i.e., the number of people it can support on a sustainable basis) depends upon land and water resources for agricultural production, but it also depends upon levels of consumption and the productivity of available technology (Marten and Sancholuz 1982). A higher level of consumption means a lower carrying capacity, but a more productive technology means a higher carrying capacity. If a population is pushing the limits of its carrying capacity, it may be stimulated to raise the carrying capacity by devising or adopting new agricultural technologies with higher levels of production per unit area, but the goal will be achieved only if the new technologies are sustainable.

As humans have achieved higher levels of agricultural production, their populations have been able to increase as carrying capacities increased. At the same time, many human societies have used internal population regulation

to maintain their populations comfortably below environmental carrying capacity, thereby reducing the role of negative forces such as limited food supplies, malnutrition, and high mortality that might otherwise act to keep their populations within the bounds of carrying capacity. Territoriality at the level of family, village, and nation has been one mechanism for internal population regulation. Other mechanisms have included infanticide and restrictions on birth rates by traditional means of family spacing. Numerous cultural changes that have occurred rapidly in recent years have disrupted traditional mechanisms of internal population regulation in many areas. Territoriality and traditional methods of birth control have often broken down and communicable diseases have been reduced, allowing the human population to increase and sometimes overshoot the carrying capacity of its environment. The consequence can be environmental degradation and human hardship when ecological forces eventually act to reduce the population to carrying capacity (Pimental and Terhune 1976).

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