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The Agroecosystem: Determinants, Resources, Processes, and Sustainability

The terms agroecosystem, farming system, and agricultural system have been used to describe agricultural activities performed by groups of people. Food system is a broader term that includes agricultural production, allocation of resources and product processing and marketing within an agricultural region and/or country (Krantz 1974). Obviously, an agroecosystem can be defined at any scale, but this book focuses primarily on agricultural systems within small geographical units. Thus, the emphasis is on interactions between people and food-producing resources within a farm or even a specific field. It is difficult to delineate the exact boundaries of an agroecosystem. Nevertheless, it should be kept in mind that agroecosystems are open systems receiving inputs from outside and producing outputs that can enter external systems (Figure 3.1).

One of the important contributions of agroecology is a list of some basic principles relating to the structure and function of agroecosystems:

1. The agroecosystem is the major ecological unit. It contains both abiotic and biotic components that are interdependent and interacting and through which nutrients are cycled and energy flows.

2. The function of agroecosystems is related to the flow of energy and the cycling of materials through the structural components of the ecosystem, which is modified through the level of input management. Energy flow refers to the initial fixation of energy in the agroecosystem by photosynthesis, its transfer through the system along a food web, and its final dissipation by respiration. Biological cycling refers to the continuous circulation of elements from an inorganic (geo) to an organic (bio) form and back again.

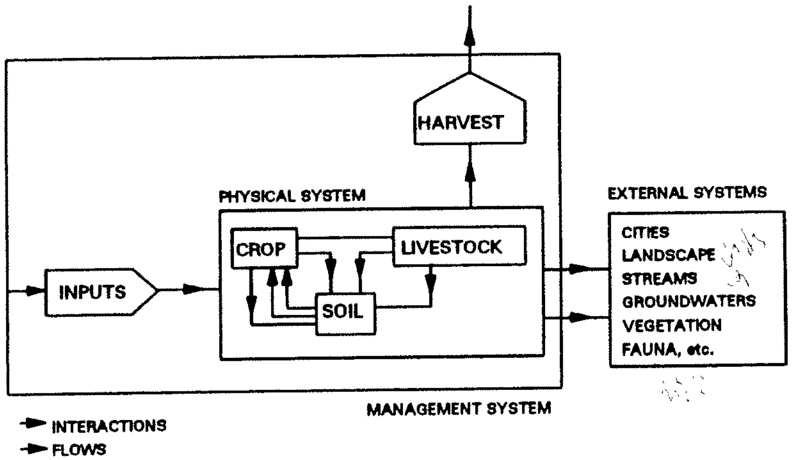

FIGURE 3.1 The general structure of an agricultural system and its relationship with external systems (after Briggs and Courtney 1985).

3. The total amount of energy that flows through an agroecosystem depends upon the amount fixed by plants or producers, and the inputs provided through management. As energy is transferred from one trophic level to another, a considerable portion is lost for further transfer. This limits the number and mass of organisms that can be maintained at each trophic level.

4. The total volume of living material can be expressed in terms of its biomass. The amount, distribution, and composition of biomass varies with type of organism, physical environment, stage of ecosystem development, and human activities. A large proportion of the organic component in most ecosystems is composed of dead organic matter (DOM), of which the largest proportion is composed of plant material.

5. Agroecosystems tend toward maturity. In so doing, they can pass from a less complex to a more complex state. This directional change is, however, inhibited in modern agriculture by maintaining monocultures characterized by low diversity and low maturity.

6. The major functional unit of the agroecosystem is the crop population. It occupies a niche in the system playing a particular role in energy flow and cycling of nutrients, although the associated biodiversity also plays key functional roles in the agroecosystem.

7. A niche within a given agroecosystem cannot be simultaneously and indefinitely occupied by a self-maintaining population of more than one species.

8. When a population reaches the limits imposed by the ecosystem, its numbers must stabilize or, failing this, decline (often sharply) from disease, pr[illegible]tion, competition, low reproduction, and so on.

Changes and fluctuations in the environment (exploitation, distur-b[illegible] competition) represent selective pressures upon the crop population.

10. Species diversity is related to the physical environment. An environment with a more complex vertical structure generally holds more species than one with a simpler structure. Thus, an agroforestry system will contain more species than a cereal system. Similarly, a benign, predictable environment holds more species than a harsher or more unpredictable environment. Tropical agroecosystems exhibit greater diversity than temperate ones.

11. In crop situations which are similar to island situations, immigration rates tend to balance extinction rates. The nearer the crop island is to a population source, the greater its immigration rate per unit time. The larger the crop island is, the higher its carrying capacity for each species. In any island situation, immigration of species declines as more species become established and fewer immigrants are new species.

Classification of Agroecosystems

Each region has a unique set of agroecosystems that results from local variations in climate, soil, economic relations, social structure, and history (Table 3.1). Thus, a survey of the agroecosystems of a region is bound to yield both commercial and subsistence agricultures, using high or low levels of technology depending on the availability of land, capital, and labor. Some technologies in the more modern systems aim at land saving (relying on biochemical inputs), while others emphasize labor saving (mechanical inputs). Traditional, resource-poor farmers usually adopt more intensive systems, emphasizing optimal use and recycling of scarce resources.

Although each farm is different, many show a family likeness and can thus be grouped together as a type of agriculture, or agroecosystem. An area with similar types of agroecosystems can then be termed an agricultural region. Whittlesay (1936) recognized five criteria to classify agroecosystems in a region: (1) the crop and livestock association; (2) the methods used to grow the crops and produce the stock; (3) the intensity of use of labor, capital, and organization, and the resulting output of product; (4) the disposal of the products for consumption (whether used for subsistence on the farm or sold for cash or other goods); and (5) the ensemble of structures used to house and facilitate farming operations.

Based on these criteria, in tropical environments it is possible to recognize seven main types of agricultural systems (Grigg 1974, Norman 1979):

1. Shifting cultivation systems
2. Semi-permanent rainfed cultivation systems
3. Permanent rainfed cultivation systems
4. Arable irrigation systems
5. Perennial crop systems

6. Grazing systems
7. Systems with regulated ley farming (alternating arable cropping and sown pasture)

Clearly these systems are always changing, forced by population shifts, resource availability, environmental degradation, economic growth or stagnation, political change, and so on. These changes can be explained by farmers' responses to variations in the physical environment, prices of inputs and products, technological innovation, and population growth. For example, Table 3.2 illustrates some of the factors that influence the change

TABLE 3.1 Agroecosystem determinants that influence the type of agriculture in each region.

Type of Determinants	Factors
Physical	Radiation Temperature Rainfall, water supply (moisture stress) Soil conditions Slope Land availability
Biological	Insect pests and natural enemies Weed communities Plant and animal diseases Soil biota Background natural vegetation Photosynthetic efficiency Cropping patterns Crop rotation
Socioeconomic	Population density Social organization Economic (prices, markets, capital, and credit availability) Technical assistance Cultivation implements Degree of commercialization Labor availability
Cultural	Traditional knowledge Beliefs Ideology Gender issues Historical events

TABLE 3.2 Factors influencing agricultural intensification in African regions where shifting cultivation is practiced (Protheroe 1972).

FACTOR	PROCESS
POPULATION	LOW DENSITY → *Increasing numbers* → HIGH DENSITY
SYSTEM	SHIFTING CULTIVATION → *Increasing length of cultivation period* → ROTATIONAL CULTIVATION/FALLOW → *Decreasing length of fallow period* → SEMI-PERMANENT/PERMANENT CULTIVATION → *Manuring and fertilizing*
CROPS	SUBSISTENCE FOOD CROPS → *Decreasing importance* → CASH (FOOD AND EXPORT) CROPS → *Increasing importance* →
TENURE	COMMUNAL RIGHT TO LAND (individual usufructory rights) → *Communal rights decreasing individual rights increasing* → INDIVIDUAL RIGHTS TO LAND Land allocation by need → Land transfer by pledge, rent, lease, and sale Fragmented/dispersed holdings → Consolidated holdings No permanent demarcation of holdings → Permanent demarcation of holdings
SETTLEMENT	IMPERMANENT/MIGRATORY SMALL VILLAGES/DISPERSED → *Increasing permanence and nucleation* → PERMANENT/FIXED NUCLEATED AND DISPERSED
EXCHANGE	NONEXISTENT/LOCAL → *Increasing involvement at local, regional, national, and international levels* MARKETS

from shifting cultivation systems to more intensive permanent systems of agriculture in Africa (Protheroe 1972).

Landscape Ecological Concepts and Agroecosystems

Landscape ecology principles are increasingly being applied to many agricultural planning issues because of the relevance of this regional approach to the planning process in landscape design and to improve both the ecology and variety of the landscape, the dispersal of species through that landscape, and the coordination of natural conservation and agricultural management (Bunce et al. 1993).

The following concepts of landscape ecology have much relevance to the design and management of agroecosystems:

Hierarchy in Landscapes. Landscapes operate at different levels involving complexes of different elements. On the one hand, one can study a whole catchment or watershed or, on the other hand, within that landscape one can examine structures such as an agricultural field, a woodland and its surrounding land covers and their relationships. An agricultural landscape in addition to fields, pastures, and orchards, contains rivers, forest patches, prairies, parks, towns, and so on. Through these landscapes there are many interactions between humans, soils, plants, and animals; water, air, nutrients, and energy, which are in constant motion. The landscape in turn changes as these processes affect each other, often over larger areas than single fields. Therefore, how crop fields and pastures are placed in a landscape can affect the quality of water, air, soils, and biodiversity in a whole agricultural region (Figure 3.2).

Gradients. Landscapes involve gradual changes and ecotones. It is recognized that many ecological elements do not show sharp boundaries between each other; rather, they grade gradually in time and space. The importance of edge effects has also been an integral feature of many studies with increases in diversity and structure. The stability and dynamics of such systems are based on physical parameters rather than on biological ones. This concept has been used in planning and nature conservation, but has not yet been applied to agroecosystems.

Biodiversity. With the increased pressure on seminatural habitats, there has been much concern about biodiversity. It is a basic concept in the management of landscapes and in planning. Policy objectives for natural parks and nature reserves are frequently formulated with the objective of maintaining an existing high biodiversity. Diversity is the outcome of historic processes and therefore refers to both time- and space- related processes. Human

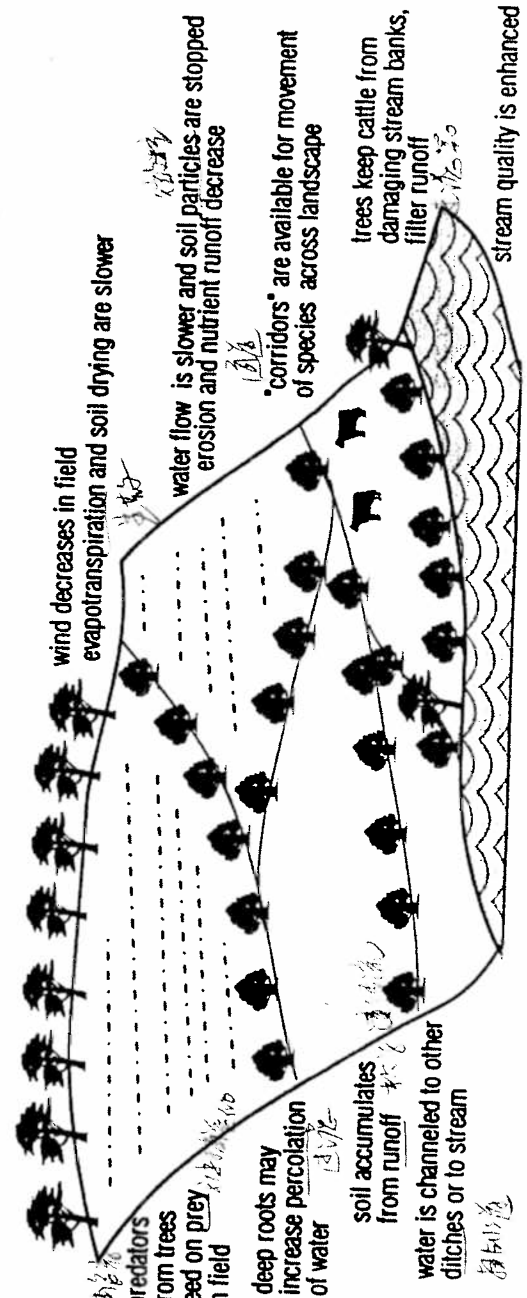

FIGURE 3.2 Effects of landscape structure on agroecological function.

activities can disturb or maintain high biodiversity, depending on the interaction of man with nature, especially by agricultural practices. Many natural and seminatural ecosystems, which once covered large areas, have been fragmented and their species are in danger.

Landscape ecology approaches are especially useful for tropical land management, as an optimal mix of land uses and conversion are needed to satisfy needs for food, fiber, and fuel as well as to conserve bioresources. Neither absolute preservation of mature forests nor complete conversions to intensively managed systems can be advocated as the solution to agricultural land management. A gradient of land uses and mosaic of forest patches and agricultural fields is the most sensible strategy to meet production and conservation needs.

Metapopulation. This represents the concept of the interrelationships between subpopulations in more or less isolated patches within a landscape and helps to understand the impact of progressive isolation of individual areas of vegetation and their associated animal populations in modern agricultural landscape. Temporary extinction and recolonization are characteristic processes of metapopulation.

The Resources of an Agroecosystem

Norman (1979) grouped the mix of resources commonly found in an agroecosystem into four categories:

Natural Resources. Natural resources are the given elements of land, water, climate, and natural vegetation that are exploited by the farmer for agricultural production. The most important elements are the area of the farm, including its topography, the degree of fragmentation of the holding, its location with respect to markets; soil depth, chemical status, and physical attributes; availability of surface water and groundwater; average rainfall, evaporation, solar radiation, and temperature (and its seasonal and annual variability); and natural vegetation, which may be an important source of food, animal feed, construction materials, or medicines for humans, and which influences soil productivity in shifting cultivation systems.

Human Resources. The human resources consist of the people who live and work within the farm and use its resources for agricultural production, based on their traditional or economic incentives. The factors affecting these resources include (a) the number of people the farm has to support in relation to the workforce and its productivity, which governs the surplus available for sale, barter, or cultural obligations; (b) the capacity for work, as influenced by nutrition and health; (c) the inclination to work, as influenced by economic status and cultural attitudes toward leisure; and (d) the flexibility of the workforce to adapt to seasonal variations in work demand, i.e., availability of hired labor and the degree of cooperation among farmers.

Capital Resources. Capital resources are the goods and services created, purchased, or borrowed by the people associated with the farm to facilitate their exploitation of natural resources for agricultural production. Capital resources can be grouped into four main categories: (a) permanent resources, such as lasting modifications to the land or water resources for the purpose of agricultural production; (b) semipermanent resources, or those that depreciate and have to be replaced periodically, like barns, fences, draft animals, implements; (c) operational resources, or consumable items used in the daily operations of the farm, like fertilizer, herbicides, manure, and seeds; and (d) potential resources, or those the farmer does not own but that may be commanded and that will eventually have to be repaid, like credit and assistance from relatives and friends.

Production Resources. Production resources include the agricultural out-put of the farm such as crops and livestock. These become capital resources when sold, and residues (crops, manure) are nutrient inputs reinvested in the system.

Ecological Processes in the Agroecosystem

Every farmer must manipulate the physical and biological resources of the farm for production. Depending on the degree of technological modification, these activities affect five major ecological processes: energetic, hydrological, biogeochemical, successional, and biotic regulation processes. Each can be evaluated in terms of inputs, outputs, storage, and transformations.

Energetic Processes

Energy enters an agroecosystem as sunlight and undergoes numerous physical transformations. Biological energy is transferred into plants by photosynthesis (primary production) and from one organism to another through the food web (consumption). Although sunlight is the only major source of energy input in most natural ecosystems, human and animal labor, mechanized energy inputs (such as plowing with a tractor), and the energy content of introduced chemicals (manures, fertilizers, and pesticides) are also significant. Human energy shapes the structure of the agroecosystem, thereby shaping energy flow through decisions about primary production and the proportion of that production that is channeled to products for human use (Marten 1986).

The various inputs into an agricultural system—solar radiation, human labor, the work of machines, fertilizers, and herbicides—can all be converted into energy values. Similarly, the outputs of the system—vegetable and animal products—can also be expressed in energy terms. As the cost and availability of fossil fuel energy is questioned, inputs and outputs are quantified for different kinds of agricultures to compare their intensity, yields, and labor productivity, and the levels of welfare they provide.

Three stages in the process of energy intensification in agriculture have been recognized (Leach 1976), examples of which can be found in different parts of the world today; (i) *pre-industrial* with only relatively low inputs of human labor; (ii) *semi-industrial*, with high inputs of human and animal power; and (iii) *full-industrial*, with very high inputs of fossil fuels and machinery. There has generally been a decline in human power associated with the rapid energy intensification of farming in the United States during the last 50 years. This process of intensification has also been accompanied by an increase in energy density. In his comparative analysis of seven types of agricultural systems, Bayliss-Smith (1982) found that the overall efficiency of energy use (energy ratio) diminishes as dependence on fossil fuels increases. Thus, in fully industrialized agriculture, the net gain of energy from agriculture is small because so much is expended in its production (Figure 3.3).

Productivity of arable crops also depends on the types and amount of energy subsidy. The variation in energy subsidies and stages in energy intensification are very clearly brought out in Table 3.3. A comparison of the energy budgets for corn (maize) production in Mexico and Guatemala with those in the United States reveals a number of important points. The yield of the latter is about three to five times that of the former. Also, as human labor is progressively replaced, first by animal power, and then by fuel and machinery, the energy dependency increases nearly 30 times, and the energy output/energy input ratio declines significantly.

Biogeochemical Processes

The major biogeochemical inputs into an agroecosystem are the nutrients released from the soil, fixation of atmospheric nitrogen by legumes, non-symbiotic nitrogen fixing (particularly important in rice growing), nutrients in rainfall and run-on water, fertilizer, and nutrients in purchased human food, stock feed, or animal manure.

The important outputs include nutrients in crops and livestock consumed on or exported from the farm. Other outputs or losses are associated with leaching beyond the root zone, denitrification and volatilization of nitrogen, losses of nitrogen and sulfur to the atmosphere when vegetation is burned, nutrients lost in soil erosion caused by runoff or wind, and nutrients in human or livestock excreta that are lost from the farm. There is also biogeochemical storage, including the fertilizer stored and manure accumulated, together with the nutrients in the soil root zone, the standing crop, vegetation, and livestock. In the course of production and consumption, mineral nutrients move cyclically through an agroecosystem. The cycles of

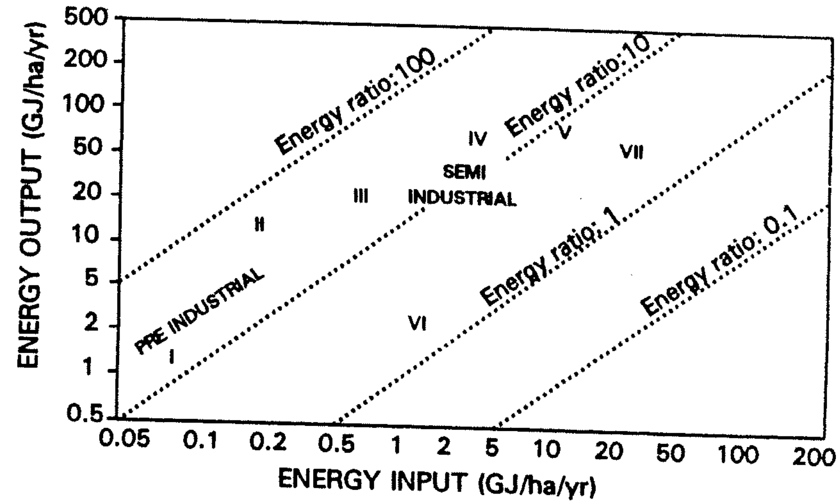

FIGURE 3.3 Inputs, outputs, and energy ratios of seven agricultural systems. I: Traditional morning farming in New Guinea (shifting cultivation, home gardens), II: British pre-industrial farming system (grain/sheep system), III: Ongoing Java agricultural system (taro, gardens, coconut, woodland, fishing), IV: South India pre-Green Revolution (sugarcane, rice, finger millet, bullock grazing), V: South India post-Green Revolution (sugarcane, rice, finger millet, bullock grazing), VII: Modern British agriculture (grains, ley, and permanent grass) (Bayliss-Smith 1982).

TABLE 3.3 Energy efficiencies of maize cropping systems under different levels of energy intensification (after Leach 1976).

System	Output/Input
Pre-industrial stage (labor intensives, Mexico)	30.6
Pre-industrial stage (labor intensives, Guatemala)	13.6
Semi-industrial stage (animal fraction, Mexico)	4.87
Full-industrial stage (mechanized, USA)	2.58

some of the most important nutrients (nitrogen, phosphorus, and potassium) are well understood in many natural and agricultural ecosystems (Todd et al. 1984). During production, elements are transferred from the soil into the plants and animals, and vice versa. Whenever carbon chains are broken apart through a variety of biological processes, nutrients are returned to the soil where they can sustain plant production (Marten 1986, Briggs and Courtney 1985).

Farmers move nutrients in and out of the agroecosystem when they bring in chemical or organic fertilizers (manure or compost) or remove the harvest or any other plant materials from the field. In modern agroecosystems, lost nutrients are replaced with purchased fertilizers. Low-income farmers who cannot afford commercial fertilizers sustain soil fertility by collecting nutrient materials from outside the crop fields, such as manure collected from pastures or enclosures in which animals are kept at night. This organic material is supplemented with leaves and other plant materials from nearby forests. In areas of Central America, farmers spread as much as 40 metric tons of litter per hectare each year over intensively cropped vegetable fields (Wilken 1977). Waste plant materials are composted with household wastes and manure from livestock.

Another strategy is to exploit the ability of the cropping system to reuse its own stored nutrients. In interplanted agroecosystems, the low disturbance and closed canopies promote nutrient conservation and cycling (Harwood 1979a). For example, in an agroforestry system, minerals lost by annuals are rapidly taken up by perennial crops. In addition, the nutrient-robbing propensity of some crops is counteracted by the addition of organic matter from other crops. Soil nitrogen can be increased by incorporating legumes in the mixture, and phosphorous assimilation can be enhanced somewhat in crops with mycorrhizal associations. Increased diversity in cropping systems is usually associated with larger root area, which increases nutrient capture.

Optimization of biogeochemical processes requires the development of optimal soil structure and fertility, which depends on:

- Regular input of organic residues
- A sufficient level of microbial activity to trigger decay of organic materials
- Conditions that ensure continual activity of earthworms and other soil-stabilizing agents
- A protective covering of vegetation

Hydrological Processes

Water is a fundamental part of all agricultural systems. In addition to its physiological role, water affects inputs of nutrients to and losses from the system through leaching and erosion. Water enters an agroecosystem as precipitation, run-on and irrigation water; it is lost through evaporation, transpiration, runoff, and drainage beyond the effective root zone of plants. Water consumed by the people and livestock on the farm may be important (such as in pastoral systems) but it is usually small in magnitude.

Water is stored in the soil, where it is used directly by crops and vegetation, in groundwater that may be drawn up for use by people, livestock, or crops, and in constructed storage such as farm ponds.

In general terms, the water balance within a particular agroecosystem can be expressed as: $S = R + Li - Et - P - Lo + So$ where *S* is the soil moisture content at the time under consideration, *R* is effective rainfall (rainfall minus interception), *Li* is the lateral flow of water into the soil, *Et* is evapotranspiration, *P* is deep percolation, *Lo* is the lateral outflow (runoff) and *So* is the original soil moisture content (Norman 1979; Briggs and Courtney 1985).

All these factors are affected by soil and vegetation conditions, and thus by agricultural practices. Agricultural drainage and tillage, for example, speed up losses by deep percolation; crop removal increases the amount of rainfall reaching the soil and reduces evapotranspiration; changes in soil structure due to tillage residue management, crop rotation, or use of manure affect rates of percolation, evapotranspiration, and lateral flow. One of the main controls of the soil moisture budget is exerted by crop cover, for it influences both inputs to and losses from soil moisture. For example, weeding reduces water losses from evapotranspiration and increases soil moisture contents.

In rainfed agriculture, it is important to know that when *R* is greater than *Et* the root zone is fully charged and defines the effective crop growing season. During this period, runoff and drainage can also occur, influencing the level of leaching of soluble nutrients, rate of soil erosion and so on. Within the range of $R = Et/2$ to $R = Et/10$, continued crop growth and maturation depend largely on the available soil water reserve or on irrigation (Norman 1979).

In most rainfed tropical areas, the agricultural potential of the area depends on the length of the rainy season and the distribution of rainfall during this period. Satisfactory crop climates are those in which rainfall exceeds actual evapotranspir-ation for at least 130 days, the length of an average growing cycle for most annual crops. The number of consecutive wet months is another important environmental criterion. The potential for sequential cropping (under rainfed conditions) is limited if there are less than five consecutive wet months (Beets 1982).

Rainfall is a major determinant of the type of crops adopted in the local cropping system. In Africa, where annual precipitation is more than 600 mm, cropping systems are generally based on maize. In tropical Asia, where precipitation is more than 1,500 mm/year with at least 200 mm/month rainfall for three consecutive months, cropping systems are generally based on rice. Since rice needs more water than other crops, and because it is the only crop that tolerates flooding, only rice is grown at the peak of the rains. A combination of upland crops can be planted at the beginning or end of the rains to use residual moisture and higher light intensities during the dry season (Figure 3.4). Mixed cropping systems such as maize and groundnuts, for example, best use the end of the rainy season (System II, Figure 3.4).

Another possibility is to combine a double and relay cropping system in which transplanted rice is established as early as possible (System III, Figure 3.4). The rice is followed by cowpeas raised using minimum tillage techniques, and cucurbits are relay-planted later (Beets 1982).

Successional Processes

Succession, the process by which organisms occupy a site and gradually change environmental conditions so that other species can replace the original inhabitants, is radically changed with modern agriculture. Agricultural fields usually represent secondary successional stages where an existing community is disrupted by deforestation and plowing, and by maintaining a simple, man-made community at the site. Figure 3.5a illustrates what happens when succession is simplified with the establishment of crop monoculture. The tendency toward complexity must be detained using agrochemical inputs (Savory 1988). By planting polycultures, the agricultural strategy accompanies the natural tendency toward complexity; enhanced crop biodiversity both above and below ground mimics natural succession and thus less external inputs are required to maintain the crop community (Figure 3.5b).

Biotic Regulation Processes

Controlling succession (plant invasion and competition) and protecting against insect pests and diseases are major problems in maintaining production continuity in agroecosystems. Farmers have used several approaches universally. These are no action, preventive action (use of resistant crop varieties, manipulation of planting dates, row spacing, modifying access of pests to plants), or successive action (chemical pesticides, biological control, cultural techniques). Ecological strategies of pest management generally employ a combination of all three approaches, aiming at making the field less attractive to pests, making the environment unsuitable to pests but favorable to natural enemies, interfering with the movement of pests from crop-to-crop or attracting pests away from crops. All these approaches will be discussed in Chapters 13, 14, and 15 as they pertain to insect, weed, and plant disease management in agroecosystems.

Scientists that perceive the agroecosystem as a result of the coevolution between social and natural processes (Norgaard and Sikor, Chapter 2) state that the above ecological processes run parallel and are interdependent with a socioeconomic flow, as the development and/or adoption of farming systems and technologies are the result of interactions between farmers and

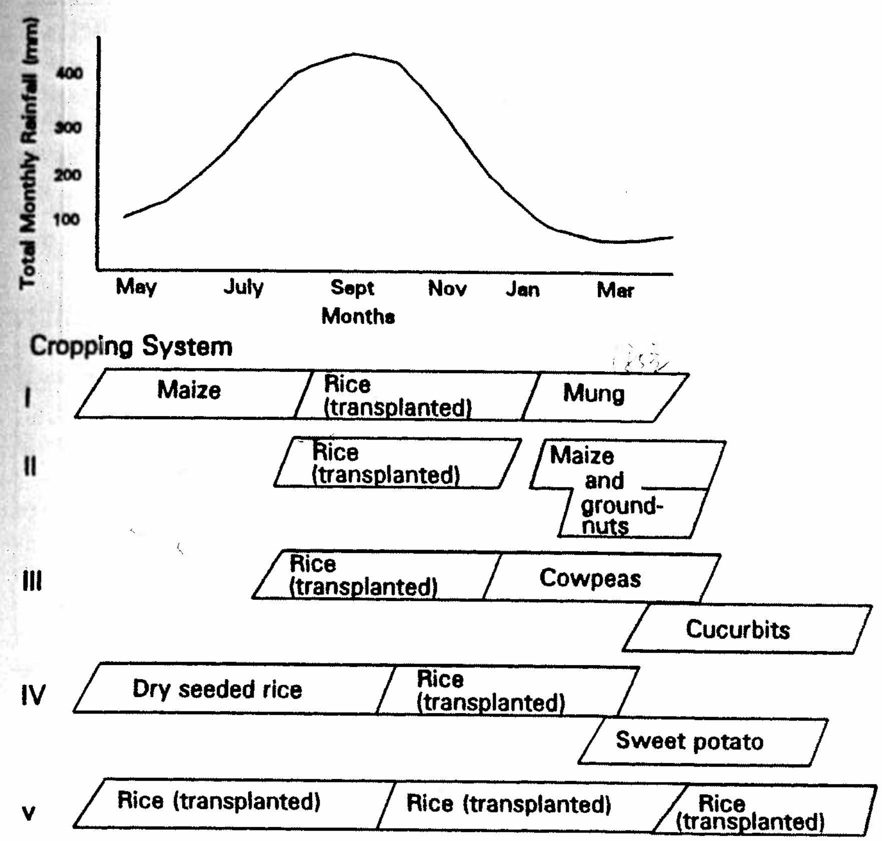

FIGURE 3.4 Five possible cropping systems that fit a rainfall pattern in Southeast Asia (Beets 1982).

their knowledge and their biophysical and socioeconomic environments. It is the understanding of this coevolution and pattern of parallel flows and interdependencies that provides the basis for study and the design of sustainable agroecosystems.

The Stability of Agroecosystems

Under conventional agriculture, humans have simplified the structure of the environment over vast areas, replacing nature's diversity with a small number of cultivated plants and domesticated animals. This process of simplification reaches an extreme form in a monoculture. The objective of this simplification is to increase the proportion of solar energy fixed by the plant communities that is directly available to humans.

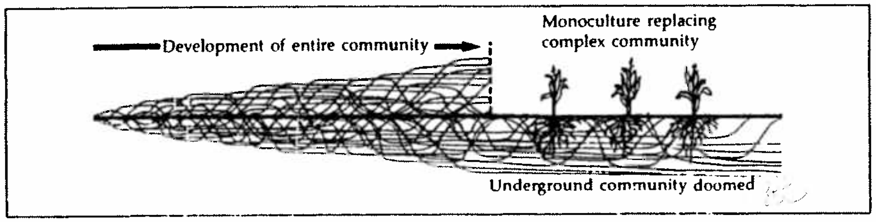

FIGURE 3.5a Disruption of natural succession to favor one population, the crop (after Savory 1988).

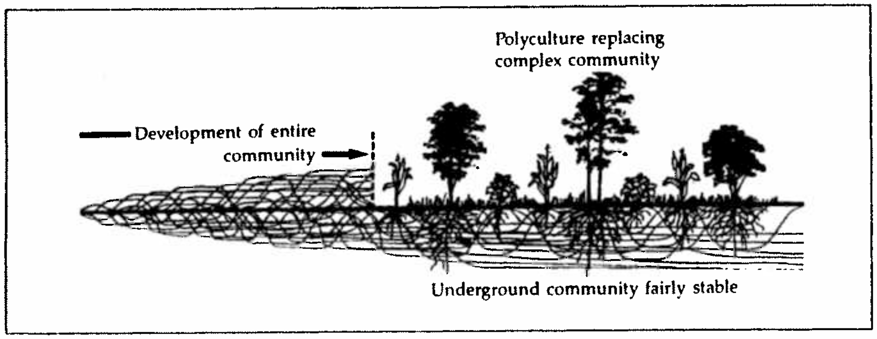

FIGURE 3.5b Improvement in population complexity with polycultures (after Savory 1988).

The dominant components are plants (and animals) selected, propagated, tended, and harvested by humans for a particular purpose. In comparison to unmanaged ecosystems, the composition and structure of agroecosystems are simple. The plant biomass is composed of stands usually dominated by one major crop plant within well-defined field boundaries. While one crop may be undersown with another, as in the case of grass under cereals or field crops or grass under orchard trees, there is normally only one layer or strata formed by the crop itself. The number of species which have been selected is remarkably few given the diversity of the world's biodiversity resources. Only some eleven plant species account for about 80 percent of the world's food supply. Among these, the cereals have dominated the development of agriculture. They provide over 50 percent of the world's production of protein and energy; over 75 percent if grains fed to animals are included. In comparison, field crops, grass/legume forage crops, and tree crops cultivated for food or forage, represent a relatively small proportion of the total agricultural biomass.

The net result is an artificial ecosystem that requires constant human intervention. Commercial seed-bed preparation and mechanized planting replace natural methods of seed dispersal; chemical pesticides replace natural controls on populations of weeds, insects, and pathogens; and genetic

manipulation replaces natural processes of plant evolution and selection. Even decomposition is altered since plant growth is harvested and soil fertility maintained, not through nutrient recycling, but with fertilizers. Although modern agroecosystems have proven capable of supporting a growing population, there is considerable evidence that the ecological equilibrium in such artificial systems is very fragile.

Why Modern Systems Are Unstable

The explanation for this potential instability must be sought in terms of changes imposed by people. These changes have removed crop ecosystems from the natural ecosystem to the extent that the two have become strikingly different in structure and function (Table 3.4). Natural ecosystems reinvest a major proportion of their productivity to maintain the physical and and biological structure needed to sustain soil fertility and biotic stability. The export of food and harvest limits such reinvestment in agroecosystems, making them highly dependent on external inputs to achieve cycling and population regulation (Cox and Atkins 1979).

It has been stated that biotic diversity and structural complexity provide a natural, mature ecosystem with a measure of stability in a fluctuating environment (Murdoch 1975). For example, severe stresses in the external physical environment, such as a change in moisture, temperature, or light are less likely to harm the entire system because in a diverse biota, numerous alternatives exist for the transfer of energy and nutrients. Hence, the system can adjust and continue to function after stress with little if any detectable disruption. Similarly, internal biotic controls (i.e., predator/prey relationships)

TABLE 3.4 Structural and functional differences between natural ecosystems and agroecosystems (modified from Odum 1969).

Characteristics	Agroecosystem	Natural Ecosystem
Net productivity	High	Medium
Trophic chains	Simple, linear	Complex
Species diversity	Low	High
Genetic diversity	Low	High
Mineral cycles	Open	Closed
Stability (resilience)	Low	High
Entropy	High	Low
Human Control	Definite	Not needed
Temporal permanence	Short	Long
Habitat heterogeneity	Simple	Complex
Phenology	Synchronized	Seasonal
Maturity	Immature, early successional	Mature, climax

prevent destructive oscillationsin pest populations, further promoting the overall stability of the natural ecosystem. The modern agricultural strategy can be viewed as a reversal of the successional sequence of nature. Modern ecosystems, despite their high yield to humankind, carry with them the disadvantages of all immature ecosystems. In particular, these systems lack the ability to cycle nutrients, conserve soil, and regulate pest popula-tions. System functioning thus depends on continued human intervention. Even crops selected for cultivation frequently cannot reproduce without the assistance of humans, through sowing, and are incapable of competing against weed species without constant control. However, there is great variability in the degree of diversity, stability, human control, and energy efficiency/productivity among the various agroecosystems (Figure 3.6).

Artificial Control in Modern Agroecosystems

To maintain normal levels of productivity in both the short term and the long term, modern agroecosystems require considerably more environmental control than organic or traditional agricultural systems (Figure 3.7). The modern systems require large amounts of imported energy to accomplish the work usually done by ecological processes in less disturbed systems. Thus, although less productive on a per-crop basis than modern monocultures, traditional polycultures are generally more stable and more energy efficient (Cox and Atkins 1979). In all agroecosystems, the cycles of land, air, water, and wastes have become open, but it occurs to a larger degree in industrialized commercial monocultures than in diversified small-scale farming systems dependent on human/animal power and local resources.

These farming systems differ not only in their levels of productivity per area or per unit of labor or input, but also in more fundamental properties. It is apparent that, while new technology has greatly increased short-term productivity, it has also lowered the sustainability, equitability, stability, and productivity of the agricultural system (Figure 3.8) (Conway 1985). Those indicators are defined as follows:

Sustainability refers to the ability of an agroecosystem to maintain production through time, in the face of long-term ecological constraints and socioeconomic pressures.

Equitability is a measure of how evenly the products of the agroecosystem are distributed among the local producers and consumers (Conway 1985). However, equity is much more than simply a matter of an adequate income, good nutrition or a satisfactory amount of leisure (Bayliss-Smith 1982). To some, equity is reached when an agroecosystem meets reasonable demands for food without increases in the social cost of production. To others, equity is reached when the distribution of opportunities or incomes within produc- communities improves (Douglass 1984).

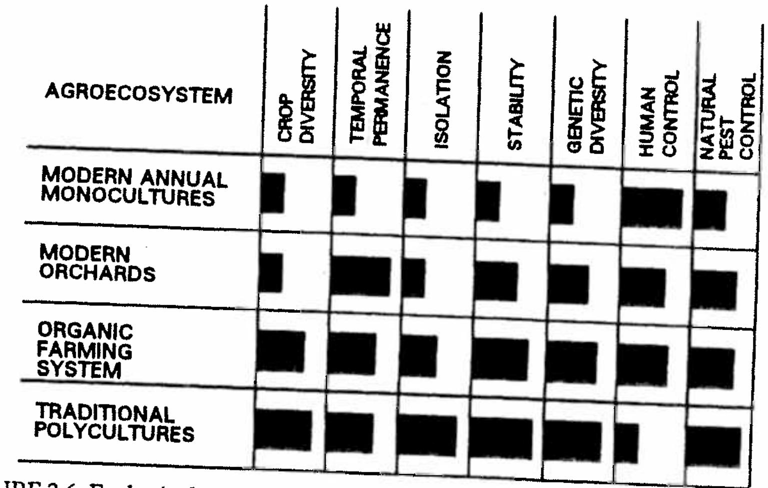

FIGURE 3.6 Ecological patterns of contrasting agroecosystems.

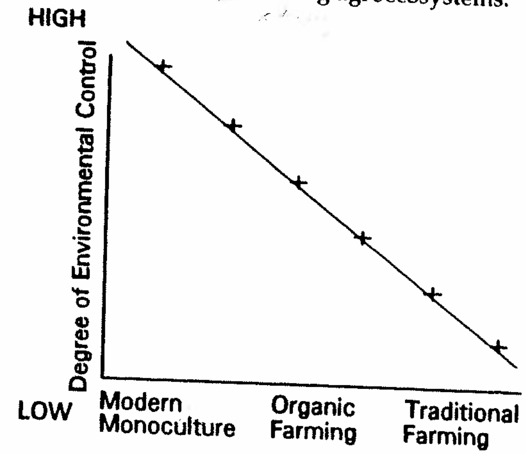

FIGURE 3.7 Degree of environmental control necessary for the maintenance of normal levels of productivity in three types of farming systems.

Stability is the constancy of production under a given set of environmental, economic and management conditions (Conway 1985). Some ecological pressures, like weather, are rigid constraints in the sense that the farmer virtually cannot modify them. In other cases, the farmer can improve the biological stability of the system by choosing more suitable crops, or developing methods of cultivation that improve yields. The land can be irrigated, mulched, manured, or rotated, or crops can be grown in mixtures to improve the resilience of the system. The farmer can supplement family labor with either animals or machines, or by employing other people's labor. Thus, the exact response depends on social factors as well as the environment.

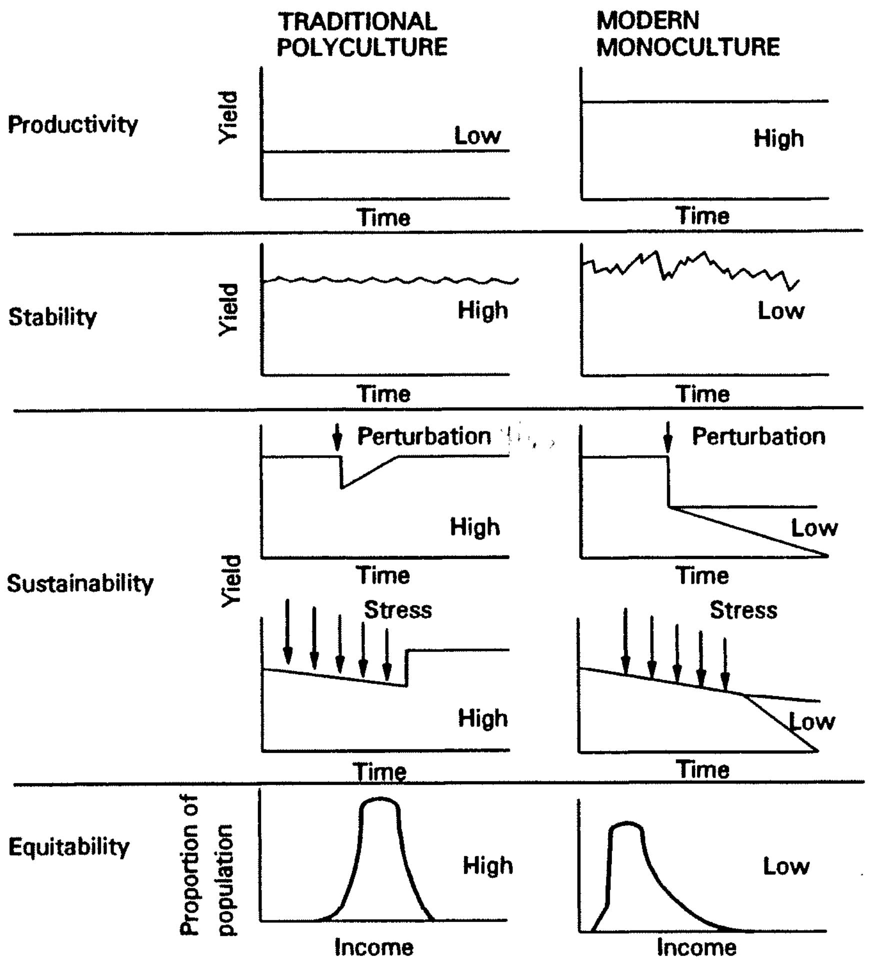

FIGURE 3.8 The system properties of agroecosystems and indices of performance (modified after Conway 1985).

For this reason, the concept of stability must be expanded to embrace socioeconomic and management considerations. In this regard, Harwood (1979a) defines three other sources of stability:

1. ***Management Stability*** is derived from choosing the set of technologies best adapted to the farmers' needs and resources. Initially, industrial technology usually increases yield, as less and less land is left fallow, and soil, water, and biotic limitations are bypassed. But there is always an element of instability associated with the new technologies. The farmers are keenly aware of this, and their resistance to change often has an ecological basis.

2. ***Economic Stability*** is associated with the farmer's ability to predict market prices of inputs and products, and to sustain farm income. Depending on the sophistication of this knowledge, the farmer will make tradeoffs between production and stability. To study the dynamics of economic stability in agricultural systems, data must be obtained on total production, yields of important commodities, cash flow, off-farm income, net income, and the fraction of total production the farmer sells or trades.

3. ***Cultural Stability*** depends on the maintenance of the sociocultural organization and context that has nurtured the agroecosystem through generations. Rural development cannot be achieved when isolated from the social context, and it must be anchored to local traditions.

Productivity is a quantitative measure of the rate and amount of production per unit of land or input. In ecological terms, production refers to the amount of yield or end product, and productivity is the process for achieving that end product. In evaluating small farm production, it is sometimes forgotten that most farmers place a higher value on reducing risk than on maximizing production. Small farmers usually are more interested in optimizing productivity of scarce farm resources than in increasing land or labor productivity. Also, farmers choose a particular production technology based on decisions made for the entire farming system, not only for a particular crop (Harwood 1979b). Yield per unit area can be one indicator of the rate and constancy of production, but it can also be expressed in other ways, such as per unit of labor input, per unit of cash investment or as energy efficiency ratios. When patterns of production are analyzed using energy ratios, traditional systems are exceedingly more efficient than modern agroecosystems (Pimentel and Pimentel 1979). A commercial agricultural system typically exhibits input/output ratios of three/one, whereas traditional farming systems exhibit ratios of 10–15/one.

The overall vulnerability of simplified modern agroecosystems is well illustrated by the epidemic of southern corn leaf blight that devastated the corn crop in the United States in 1970 and the destruction of millions of tons of wheat in the midwestern states in 1953 and 1954 by race 15B of *Puccinia graminis* f. sp. *tritici* (Baker and Cook 1974). The potato late-blight epidemic and subsequent famine in Ireland in the mid-19th century is a strong reminder that growing vast acreages of a highly simplified commodity is not a dependable means of food production. An alarming picture emerges from a report prepared by the National Research Council of the National Academy of Sciences on the extent to which many staple crops have become genetically uniform and vulnerable to epidemics (Adams et al. 1971). This trend toward uniformity is apparent in the post-Green Revolution tendency of farmers to plant a single high-yielding variety in place of several different traditional varieties.

The intensification of agriculture is a crucial test of the resiliency of nature.

How much longer humans can keep increasing the magnitude of nature's subsidy without depleting natural resources and causing further environmental degradation is uncertain. Before discovering this critical point through unfortunate experience, one must endeavor to design agroecosystems that compare in stability and productivity with natural ecosystems (Cox and Atkins 1979). This is the driving force of agroecology.

Evaluating the Ecological Status and Sustainability of Agroecosystems

Most definitions of sustainability include at least three criteria:

- Maintenance of the productive capacity of the agroecosystem
- Preservation of the floral and faunal diversity
- The ability of the agroecosystem to maintain itself

An important feature of sustainability is the capacity of the agroecosystem to maintain a non-declining yield over time, within a broad range of conditions. Most concepts of sustainability require both continued yield and the avoidance of environmental degradation. These two demands are often pictured as mutually incompatible. Agricultural production depends on resource utilization, while environmental protection requires an acceptable extent of conservation. The problem is that there is a transition period before sustainability is reached and, thus, return on investment in agroecological techniques may not be immediately realized (Figure 3.9). The challenge is to assess the health of agroecosystems to ensure a balanced monitoring of the productivity and ecological integrity of the system. Historically, monitoring of agricultural systems has focused on quantifying the production of food and fiber and to some extent on the status, condition, and trends of soil, water, and related resources. Monitoring of the status of critical biological components or processes of agroecosystems has been sorely lacking. In an attempt to develop a more holistic approach to assess the agroecological condition of agroecosystems, Meyer et al. (1992) identified three assessment endpoints which constitute quantifiable expressions of environmental change. The assessment endpoints are:

Sustainability. Capacity to maintain a level of crop productivity over time without jeopardizing the structural and functional components of agroecosystems.

Contamination of Natural Resources. Alteration of the quality of air, water, and soil by inputs or outputs from agroecosystems.

Quality of the Agricultural Landscape. Various ways in which agricultural land use patterns modify the landscape and influence ecological processes. Indicators currently being considered for agroecological monitoring are

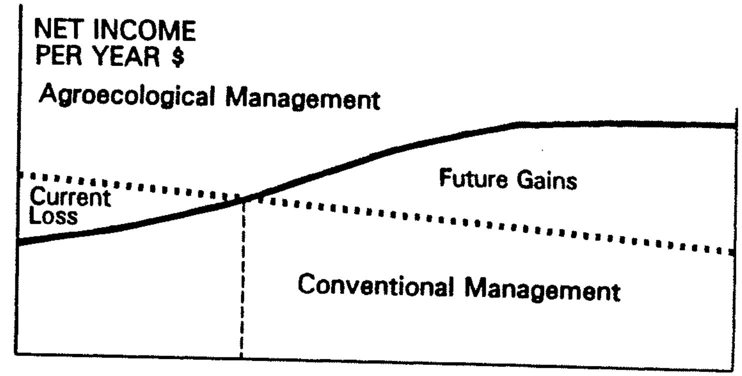

FIGURE 3.9 Comparison of the flows of net incomes from two land-use practices, agroecological versus conventional management (after Roberts 1992).

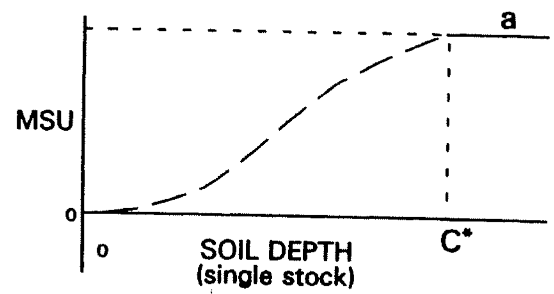

FIGURE 3.10 The general relationship between the maximum sustainable level of use (MSU) of soil and its depth.

shown in Table 3.5 in association with the assessment endpoints.

Among the indicators, six important indicators were selected for initial evaluation:

Crop Productivity. Estimate of the efficiency of the inputs in achieving desired yield and also for beneficial or detrimental environmental inputs and outputs.

Soil Productivity. Resource renewal of the soil, which is necessarily degraded in the extraction of value from it; the maximum sustainable level of use (MSU) is equivalent to its renewal rate. The curve in Figure 3.10 describes a general relationship between the MSU of agricultural soil and the stock (soil depth). While soil depth remains sufficiently greater than the rooting depth of crops or other plants, soil loss has little or no negative effect on productivity, but productivity decreases with soil depth below this threshold. Initially negligible costs of losing soil to erosion become steep as soil thins below this threshold (called the critical point, C*).

TABLE 3.5 Association between agroecosystem assessment endpoints and indicators (Meyer et al. 1992).

Indicator	Sustainability	Contamination of natural	Quality of agricultural
Crop productivity	X		
Soil productivity	X	X	
Nutrient-holding capacity	X		
Erosion	X		
Contaminants	X	X	
Microbial component	X	X	
Land use	X		
Landscape descriptors	X	X	X
Wildlife populations			X
Beneficial insect density	X		X
Pest density	X		
Status of biomonitor species		X	
Irrigation water quantity	X		
Irrigation water quality	X	X	
Agricultural chemical use	X	X	
Non-point source loading		X	
Foliar symptoms	X	X	
Livestock production	X		
Socioeconomic factors	X		
Genetic diversity	X		

[a] Air, soil, water, and biota, including transport of contaminants into, within, and out of agroecosystems.

In practical terms, soil productivity is characterized by the nutrient-holding capacity, soil biota, extent of contamination, and rate of erosion.

Irrigation Water Quantity and Quality. Two aspects will be addressed: (1) the impacts of water quality and quantity on the ecological condition of irrigated agroecosystems and (2) the impacts of agroecosystem management on water quality and quantity.

Abundance and Diversity of Beneficial Insects. The occurrence and prevalence of predators, parasites, and pollinators.

Agricultural Chemical Use. Effects on crop yields and on non-target sectors of the agroecosystem and adjacent ecosystems.

Genetic Diversity. The level of intra- and interspecific genetic diversity maintained, and rates of crop genetic erosion.

Utilizing another set of biophysical and socioeconomic indicators, scientists (NRC 1993) evaluating various attributes of tropical agroecosystems arrived at a framework for comparing the attributes and potential contributions to sustainability of various land use systems (Table 3.6). Although various physicochemical, biological, social, cultural, and economic factors are used to analyze system performance and potential, it is recognized that many aspects of agricultural sustainability are difficult to categorize and quantify and, therefore, these qualitative values are offered for each attribute.

One of the few attempts made at quantifying sustainability is the study of Faeth et al. (1991), which compares the economics of conventional and alternative production systems in Pennsylvania and Nebraska when natural resources are accounted for, in particular, soil depreciation. The authors used a method of natural resource accounting using economic data to provide a relatively simple way to arrive at quantitative measures of sustainability. Soil productivity, farm profitability, regional environmental impacts, and government fiscal costs can all be included within the natural resource accounting framework.

Tables 3.7a and b compare net farm income and net economic value per acre for Pennsylvania's best conventional corn-soybean rotation, with and without natural resource accounting. Table 3.7, column 1, shows a conventional financial analysis of net farm income. The gross operating margin, crop sales less variable production costs, is shown in the first row ($45). Because conventional analyses make no allowance for natural resource depletion, the gross margin and net farm operating income are the same. Government subsidies ($35) are added to obtain net income ($80). When natural resource accounts are included, the gross operating margin is reduced by a soil depreciation allowance ($25) to obtain net farm income ($20) (Table 3.7a). The depreciation allowance is an estimate of the present value of future income losses due to the impact of crop production on soil quality. The same government payment is added to determine net farm income ($55).

Net economic value subtracts $47 as an adjustment for off-site environmental costs (such as sedimentation, impacts on recreation, and fisheries, and

TABLE 3.6 Comparison of the biophysical, social, and economic attributes of land use systems in the humid tripics[a] (NRC 1993).

	Biophysical Attributes														
	Nutrient Cycling Capacity[b]			Soil and Water Conservation Capacity			Stability Towards Pests and Diseases[g]			Biodiversity Level[h]			Carbon Storage		
Land Use Systems	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Intensive cropping															
High-resource areas		X[e]	X[f]		X		X	O		X			X		
Low-resource areas	X	O		X	O		X	O		X	O		X		
Low-intensity shifting cultivation	X			X	O		X				X		X	O	
Agropastoral systems		X			X	O		X			X			X	
Cattle ranching	X			X	O			X		X	O[i]		X	O	
Agroforestry		X			X			X		X	O			X	
Mixed tree systems			X		X	O		X			X			X	O
Perennial tree crop plantations			X		X	O	X			X				X	
Plantation forestry			X		X	O	X	O		X				X	O
Regenerating and secondary forests			X		X	O		X			X			X	O
Natural forest management			X			X		X			X			X	O
Modified forests			X			X		X			X				X
Forest reserves			X			X			X			X			X

NOTE: The letter L (low), M (moderate), and H (high) refer to the level at which a given land use would reflect a give attribute.

[a] In this assessment, "X: denotes results using the best widely available technologies for each land use sytem. The "O" connotes the results of applying best technologies now under limited-location research or documentation. The systems could have the characteristics denoted by "O" given continued short-term (5-10 year period) reseaarch and extension.

[b] The capacity to cycle nutrients from the soil to economically useful plants or animals and replenish them without significant loss to the environment.

[c] Those areas with fertile soils and little slope and few, if any, restriction to agricultural land use. They have adequate rainfall or irrigation during much of the year for crop growth.

[d] High efficiency of recycling but low levels of nutrient removal through harvesting.

[e] Present technologies may develop high flow with high crop production, but they often entail high nutrient loss. Future technologies hold promise for greater containment and efficiency.

[f] Lowland, flooded rice production has both high nutrient flow and very high efficiency of reycling and of nutrient containment.

TABLE 3.6 *continued*

	Social Attributes									Economic Attributes								
	Health and Nutritional Benefits[j]			Cultural and Communal Viability[k]			Political Acceptability[l]			Required External Inputs[m]			Employment Per Land Unit			Income		
Land Use Systems	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Intensive cropping																		
High-resource areas		X	O			X			X			X			X			X
Low-resource areas		X	O		X	O		X	O		X			X	O	X	O	
Low-intensity shifting cultivation			X		X			X			X				X		X	
Agropastoral systems		X	O		X	O		X	O		X			X	O		X	
Cattle ranching	X	O			O				X		X		X				X	
Agroforestry		X			X	O		X	O		X		X	O		X	O	
Mixed tree systems	X	O		X	X	O		X	O	X	O		X	O		X	O	
Perennial tree crop plantations	X				X				X			X[n]		X				X
Plantation forestry	X				X				X		X	X[n]						
Regenerating and secondary forests	X				X			X		X				X		X	X	
Natural forest management	X				X	O		X	O		X			X			X	
Modified forests	X	O			X			X		X	O			X		X		
Forest reserves				X				X		X						X		

[g] Indicates the natural ability to maintain pests and diseases below economic threshold levels in tropical ecosystems.

[h] Refers to the diversity of plant and crop species which, in turn, fosters diversity of flora and fauna both above and below the ground.

[i] Assumes diversity of plant species under well-managed grazing systems, which may include tree species in silvipastoral systems.

[j] To farms and their local communities.

[k] The ability to survive as a land use system, to provide income, employment, and the neded goods in communities under continued and increasing population pressure. The systems must make optimum use of local resources and encourage acceptable levels of local equity.

[l] Politically desirable at levels above the local community (that is, county, region, province, state, or national level). At higher government levels it is assumed that generating cash flow through national or international channels usually takes precedence, but with the we-being of local communities having increasing consideration.

[m] Levels of external inputs appropriate to maintain optimal production with best available technologies. These levels, particularly of pesticides, may not be environmentally sustainable in the long term.

[n] Includes capital investment for establishment.

impacts on down-stream water users). Net economic value also includes the on-site soil depreciation allowance, but excludes income support payments (Table 3.7b). Farmers do not bear the off-site costs directly, but they are nonetheless real economic costs attributable to agricultural production and should be considered in calculating ne teconomic value.

Subsidy payments, by contrast, are a transfer from taxpayers to farmers, not income generated by agricultural production, and are therefore excluded from net economic value calculations. In this example, when these adjustments are made, an excluded from net economic value calculations. In this example, when these adjustments are made, an $80 profit under conventional financial accounting becomes a $27 loss under more complete economic accounting.

TABLE 3.7a Conventional and natural resource accounting economic frameworks compared.

NET FARM INCOME ($/acre/year)

	w/o Natural Resource Accounting	w/ Natural Resource Accounting
Gross Operating Margin	45	45
- Soil Depreciation	–	25
Net Farm Operating Income	45	20
+ Government Commodity Subsidy	35	35
Net Farm Income	80	55

TABLE 3.7b Conventional and natural resource accounting economic frameworks compared.

NET FARM INCOME ($/acre/year)

	w/o Natural Resource Accounting	w/ Natural Resource Accounting
Gross Operating Margin	45	45
- Soil Depreciation	–	25
Net Farm Operating Income	45	20
- Off-site Costs	–	47
Net Economic Value	80	-27

PART TWO

The Design of Alternative Agricultural Systems and Technologies