Agroecology
SECOND EDITION

Agroecology
The Science of Sustainable Agriculture

Miguel A. Altieri

with contributions by
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I dedicate this book to my late mother, Adriana Soto, who gave me life and light and who unfortunately left the world before seeing this last edition. This book is also dedicated to Naraya and Joshua Altieri, my children and companions.
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Since the publication of the first edition of this book in 1987, there has been an explosive worldwide interest in searching for more sustainable ways of producing food. Hundreds of research projects and technological development attempts have taken place, and many lessons have been learned. However, much of the emphasis is still highly technological, focusing on an input substitution approach in order to replace costly and degrading agrochemical and high-input technologies for more environmentally sound, low-external input technologies. There still prevails a narrow view that specific causes affect productivity, and, overcoming this limiting factor via alternative technologies continues to be the main goal. This view has diverted agriculturalists from an appreciation of the context and complexity of agroecological processes.

In the search to reinstate a more ecological rationale into agricultural production, scientists and developers have disregarded a key point in the development of a more self-sufficient and sustaining agriculture: a deep understanding of the nature of agroecosystems and the principles by which they function. Based on new research results and practical findings, I attempt in this edition to re-emphasize the importance of agroecology as the discipline that provides the basic ecological principles for how to study, design, and manage agroecosystems that are both productive and natural resource conserving, and are also culturally sensitive, socially just, and economically viable.

Agroecology goes beyond a one-dimensional view of agroecosystems — their genetics, agronomy, edaphology—to embrace an understanding of ecological and social levels of coevolution, structure, and function. Agroecology encourages researchers to tap into farmers' knowledge and skills and to identify the unlimited potential of assembling biodiversity to create beneficial synergisms that provide agroecosystems with the ability to remain or return to an innate state of natural stability. Sustainable yield in the agroecosystem derives from the proper balance of crops, soils, nutrients, sunlight, moisture, and other coexisting organisms. The agroecosystem is productive and healthy when these balanced and rich growing conditions
prevail and when crop plants remain resilient to tolerate stress and adversity. Occasional disturbances can be overcome by a vigorous agroecosystem which is adaptable and diverse enough to recover once the stress has passed. Occasionally, strong measures (i.e., botanical insecticides, alternative fertilizers, etc.) may need to be applied by farmers employing alternative methods to control specific pests or soil problems. Agroecology provides the guidelines to carefully manage agroecosystems without unnecessary or irreparable damage. Simultaneous with the struggle to fight pests, diseases, or soil deficiency, the agroecologist strives to restore the resiliency and strength of the agroecosystem. If the cause of disease, pests, soil degradation, and so forth, is understood as imbalance, then the goal of the agroecological treatment is to recover balance. In agroecology, biodiversification is the primary technique to evoke self-regulation and sustainability.

However, ecological health is not the only goal of agroecology. In fact, sustainability is not possible without preserving the cultural diversity that nurtures local agricultures. Stable production can only take place within the context of a social organization that protects the integrity of natural resources and nurtures the harmonious interaction of humans, the agroecosystem, and the environment.

This second edition incorporates new insights and concepts in the hope of helping guide agricultural students, researchers, and practitioners to a deeper understanding of the ecology of agricultural systems that will open the doors to new management options more in tune with the objectives of a truly sustainable agriculture.

_Miguel A. Altieri_
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M. A. A.
PART ONE

The Theoretical Basis of Agricultural Ecology
The contemporary use of the term agroecology dates from the 1970s, but the science and the practice of agroecology are as old as the origins of agriculture. As researchers explore indigenous agricultures, which are modified relics of earlier agronomic forms, it is increasingly apparent that many locally developed agricultural systems routinely incorporate mechanisms to accommodate crops to the variability of the natural environment and to protect them from predation and competition. These mechanisms make use of regionally available renewable inputs and ecological and structural features of the agricultural field, fallows, and surrounding vegetation.

Agriculture in these situations involves managing resources other than the "target" crop. These production systems were developed to balance out environmental and economic risk and maintain the productive base of agriculture over time. While such agroecosystems can include infrastructure like terraces, trenches, and irrigation works, the decentralized, locally developed agronomic knowledge is central to the continuing performance of these production systems.
Why this agricultural heritage has been relatively unimportant in the formal agronomic sciences reflects biases that some contemporary researchers are trying to overcome. Three historical processes have done much to obscure and denigrate the agronomic knowledge that was developed by local peoples and non-western societies: (1) the destruction of the means of encoding, regulating, and transmitting agricultural practices; (2) the dramatic transformation of many non-western indigenous societies and the production systems on which they were based as a result of demographic collapse, slaving, and colonial and market processes; and (3) the rise of positivist science. As a result, there have been few opportunities for the insights developed in a more holistic agriculture to "filter up" into the formal scientific community. This difficulty is further compounded by unrecognized biases of agronomic researchers related to social factors such as class, ethnicity, culture, and gender.

Historically, agricultural management included rich symbolic and ritual systems that often served to regulate land use practices, and to encode the agrarian knowledge of non-literate peoples (Ellen 1982, Conklin 1972). The existence of agrarian cults and ritual has been documented for many societies, including those of Western Europe. Indeed, these cults were an essential focus of the Catholic Inquisition. Medieval social historians such as Ginzburg (1983) have shown how rural ceremonies were branded as witchcraft, and how such activities became the focus for intense persecution. Not surprisingly, as the post-Inquisition Spanish and Portuguese explorers set sail and European conquest spread over the globe for "God, gold, and glory," part of their larger project included evangelical activities that often altered the symbolic and ritual bases of agriculture in non-western societies. These modifications transformed and often interfered with the generational and lateral transfer of local agronomic knowledge. This process, along with diseases, slaving, and the frequent restructuring of the agricultural base of rural communities for colonial and market purposes, often contributed to the destruction or abandonment of the "hard" technologies such as irrigation systems and especially to the impoverishment of "soft" technologies (cultivar types, cropping mixes, techniques of biological control, and soil management) of the local agricultures, which were far more dependent on cultural forms of transmission.

It is well documented how the diseases carried by explorers affected native populations. Especially in the New World, where rapid devastation of populations occurred. As much as 90 percent of the population of some areas died in less than 100 years (Denevan 1976). With them died cultures and knowledge systems. The grisly effects of epidemics characterized the earlier phases of contact, but other activities, especially slaving for New World plantations, were also to have drastic impacts on population and thus on agricultural knowledge until well into the 19th century.
Initially, local populations were the focus of slave raids, but these groups were often able to escape from bondage. The disease problems of the New World Indians also made them a less than ideal labor force. African populations, on the other hand, were accustomed to tropical conditions and were relatively resistant to "European" diseases. They could thus satisfy the burgeoning manpower needs of sugar and cotton plantations. Over two centuries more than 20 million slaves were transported from Africa to various slave plantations in the New World.

Slaving was directed at the best labor force (young adult men and women) and it resulted in the loss of this important labor force for local agriculture and the abandonment of agricultural works as people sought to avoid slavery by moving to areas distant from slavers. The disruption of knowledge systems through the export of labor, the erosion of the cultural basis of local agricultures, and the mortality associated with warfare stimulated by slaving raids was later compounded by the integration of these residual systems into mercantile and colonial networks.

The European contact with much of the non-western world was not benign and often involved the transformation of productive systems to satisfy the needs of local bureaucratic centers, mining or resource enclaves, and international commerce. This was achieved through direct coercion in some cases, reorienting or manipulating economies through the collusion of existing local elites and headmen in others, and through exchange. These processes fundamentally changed the basis of the agricultural economy. With the emergence of cash cropping and increased pressure on particular export items, rural land use strategies that had evolved over millennia to reduce agricultural risk and maintain the resource base were destabilized. Many studies have documented these effects (Watts 1983, Wolf 1982, Palmer and Parsons 1977, Wasserstrom 1982, Brokenshaw et al. 1979, Geertz 1962).

Finally, even when chroniclers and explorers made positive mention of native land use practices, it was difficult to translate these observations into a coherent, non-folkloric and socially acceptable form. The rise of the positivist method in science and the movement of western thought to atomistic and mechanistic perspectives associated with the 18th century enlightenment dramatically altered the discourse about the natural world (Merchant 1980).

This transition in epistemologies shifted the view of nature from that of an organic, living entity to one of a machine. Increasingly, this approach emphasized a language of science, a way of talking about the natural world that essentially dismissed other forms of scientific knowledge as superstitions. Indeed, from the time of Condorcet and Comte, the rise of science was equated with the triumph of reason over superstition. This position, coupled with an often derogatory view of the abilities of rural peoples generally, and colonized populations in particular, further obscured the
richness of many rural knowledge systems whose content was expressed in
discursive and symbolic form. Because the ecological context was misunder-
stood, the spatial and cultivar complexity of non-formalized agricultures was
frequently reviled as disorder.

Given this history, one might ask how agroecology managed to re-emerge
at all. The "rediscovery" of agroecology is an unusual example of the impact
of pre-existing technologies on the sciences, where critically important
advances in the understanding of nature resulted from the decision of
scientists to study what farmers had already learned how to do (Kuhn 1979).
Kuhn points out that in many cases, scientists succeeded in "merely
validating and explaining, not in improving, techniques developed earlier."

How the idea of agroecology re-emerged also requires the analysis of the
influence of a number of intellectual currents that had relatively little to do
with formal agronomy. The study of indigenous classification systems, rural
development theory, nutrient cycling, and succession has little direct relation
to crop science, soil science, plant pathology, and pest management as they
are normally practiced. How disciplines as diverse as anthropology,
economics, and ecology are reflected in the intellectual pedigree of agro-
ecology is outlined briefly in the next sections in this chapter, but the entire
volume shows the influences on agroecological approaches in far more
detail.

What Is Agroecology?

The term agroecology has come to mean many things. Loosely defined,
agroecology often incorporates ideas about a more environmentally and
socially sensitive approach to agriculture, one that focuses not only on
production, but also on the ecological sustainability of the production
system. This might be called the "normative" or "prescriptive" use of the term
agroecology, because it implies a number of features about society and
production that go well beyond the limits of the agricultural field. At its
most narrow, agroecology refers to the study of purely ecological phenome-
na within the crop field, such as predator/prey relations, or crop/weed
competition.

The Ecological View

At the heart of agroecology is the idea that a crop field is an ecosystem in
which ecological processes found in other vegetation formations such as
nutrient cycling, predator/prey interactions, competition, commensalism,
and successional changes also occur. Agroecology focuses on ecological
relations in the field, and its purpose is to illuminate the form, dynamics, and
function of these relations. Implicit in some agroecological work is the idea
that by understanding these processes and relations, agroecosystems can be manipulated to produce better, with fewer negative environmental or social impacts, more sustainably, and with fewer external inputs. As a result, a number of researchers in the agricultural sciences and related fields have begun to view the agricultural field as a particular kind of ecosystem—an agroecosystem—and to formalize the analysis of the ensemble of processes and interactions in cropping systems. The underlying analytic framework owes much to systems theory and the theoretical and practical attempts at integrating the numerous factors that affect agriculture (Spedding 1975, Conway 1981a and 1981b, Gliessman 1982a, Conway 1985, Chambers 1983, Ellen 1982, Altieri 1983, Lowrance et al. 1984).

The Social Perspective

Agroecosystems have various degrees of resiliency and stability, but these are not strictly determined by biotic or environmental factors. Social factors such as a collapse in market prices or changes in land tenure can disrupt agricultural systems as decisively as drought, pest outbreak, or soil nutrient decline. On the other hand, decisions that allocate energy and material inputs can enhance the resiliency and recuperation of damaged ecosystems. Although human manipulations of ecosystems for agricultural production have often dramatically altered the structure, diversity, patterns of energy, and nutrient flux and mechanisms of population regulation within agricultural fields, these processes still operate and can be explored experimentally. The magnitude of the differences in ecological function between a natural and an agricultural ecosystem depends tremendously on the intensity and frequency of the natural and human perturbations that impinge on an ecosystem. The results of the interplay between endogenous biological and environmental features of the agricultural field and exogenous social and economic factors generate the particular agroecosystem structure. For this reason, a broader perspective is often needed to explain an observed production system.

An agricultural system differs in several fundamental ways from a "natural" ecological system in its structure and function. Agroecosystems are semi-domesticated ecosystems that fall on a gradient between ecosystems that have experienced minimal human impact, and those under maximum human control, like cities. Odum (1984) describes four major characteristics of agroecosystems:

1. Agroecosystems include auxiliary sources of energy like human, animal and fuel energy to enhance productivity of particular organisms.
2. Diversity is greatly reduced compared with many natural ecosystems.
3. The dominant animals and plants are under artificial rather than natural selection.
4. The system controls are external rather than internal via subsystem feedback.

Odum’s model is primarily based on modern agriculture, as found in the United States. There are, however, many kinds of agricultural systems, particularly in the tropics, that do not fit this definition. Particularly suspect are questions of diversity and the nature of selection in complex agricultures when a number of semi-domesticates and wild plants and animals figure into the production system. For example, Conklin (1956) described agroecosystems in the Philippines that included over 600 cultivated and managed plants. While this agriculture was not as diverse as some tropical forests, it was certainly more diverse than many other local ecosystems.

Agricultural systems are complex interactions between external and internal social, biological, and environmental processes. These can be understood spatially at the level of the agricultural field, but often include a temporal dimension as well. The degree of external vs. internal control can reflect intensity of management over time, which can be far more variable than Odum suggests. In swidden systems, for example, external controls tend to drop off in the later fallow periods. Odum’s model of agroecosystems is an interesting point of departure for understanding agriculture from an ecological systems perspective, but cannot capture the diversity and complexity of many agroecosystems that evolved in non-Western societies, particularly in the humid tropics. Moreover, the model’s lack of attention to the social determinants of agriculture results in a model with limited explanatory power.

Agricultural systems are human artifacts, and the determinants of agriculture do not stop at the boundaries of the field. Agricultural strategies respond not only to environmental, biotic, and cultivar constraints, but also reflect human subsistence strategies and economic conditions (Ellen 1982). Factors like labor availability, access and conditions of credit, subsidies, perceived risk, price information, kinship obligations, family size, and access to other forms of livelihood are often critical to understanding the logic of farming systems. Particularly when analyzing situations of small farmers outside the U.S. and Europe, simple yield maximization in monocultural systems becomes less useful for understanding farmer behavior and agronomic choices (Scott 1978 and 1986, Bartlett 1984, Chambers 1983).

The Agroecology Challenge

Conventional agricultural scientists have been concerned primarily with the effect of soil, animal, or vegetation management practices upon the
productivity of a given crop, using a perspective that emphasized a target problem such as soil nutrients or pest outbreaks. This means of addressing agricultural systems has been determined in part by the limited dialogue across disciplinary lines, by the structure of scientific investigation, which tends to atomize research questions, and by an agricultural commodity focus. There is no question that agricultural research based on this approach has been successful in increasing yields in favored situations.

Increasingly, however, scientists are recognizing that such a narrow approach could limit agricultural options for rural peoples, and that the "target approach" often carries with it unintended secondary consequences that have often been ecologically damaging and had high social costs. Agroecology research does concentrate on target issues in the agricultural field, but within a wider context that includes ecological and social variables. In many cases, premises about the purposes of an agricultural system may be at variance with the purely productionist or yield focus of some agricultural scientists.

Agroecology can best be described as an approach that integrates the ideas and methods of several subfields, rather than as a specific discipline. Agroecology can be a normative challenge to existing ways of approaching agricultural issues in several disciplines. It has roots in the agricultural sciences, in the environmental movement, in ecology (particularly in the explosion of research on tropical ecosystems), in the analysis of indigenous agroecosystems, and in rural development studies. Each of these areas of inquiry has quite different aims and methodologies, yet taken together, they have all been legitimate and important influences on agroecological thought.

Influences on Agroecological Thought

Agricultural Sciences

As Altieri (1983) has pointed out, credit for much of the initial development of agricultural ecology in the formal sciences belongs to Klages (1928), who suggested that consideration be given to the physiological and agronomic factors influencing the distribution and adaptation of specific crop species to understand the complex relationships between a crop plant and its environment. Later Klages (1942) broadened his definition to include the historical, technological, and socioeconomic factors that determined what crops could be produced in a given region and in what amount. Papadakis (1938) stressed that the culture of crops should be based on the crops' response to environment. Agricultural ecology was defined further in the 1960s by Tischler (1965) and integrated into the agricultural curriculum in which courses were oriented to designed for an ecological point of view on crop adaptation. Agronomy and crop ecology are increasingly converging,
but the networks between agronomy and the other sciences (including social sciences) necessary for agroecological work are just coming into being.

The works of Azzi (1956), Tischler (1965), Chang (1968), and Loucks (1977) represent the gradual shift toward an ecosystem approach to agriculture. Azzi (1956) in particular emphasized that while meteorology, soil science, and entomology are distinct disciplines, their study in relation to the potential responses of crop plants converges in an agroecological science that should illuminate the relationships between crop plants and their environment. Wilsie (1962) analyzed the principles of crop adaptation and distribution in relation to habitat factors and made an attempt to formalize the body of relationships implicit in crop systems. Chang (1968) further pursued the lines suggested by Wilsie, but focused on the ecophysiological aspects.


Pest managers, particularly entomologists, have made important contributions to the development of an ecological perspective in plant protection. The theory and practice of biological pest control is based on ecological principles (Huffaker and Messenger 1976). Ecological pest management focuses primarily on approaches that contrast the structure and function of agricultural systems with those of relatively undisturbed systems or more complex agricultural systems (Southwood and Way 1970, Price and Waldbauer 1975, Levins and Wilson 1979, Risch 1981 and Risch et al. 1983). Browning and Frey (1969) have argued that pest management approaches should emphasize the development of agroecosystems that emulate later successional stages as much as possible, since these types of systems are often more stable than systems of simple monocultural structure.

**Methodological Approaches**

A great deal of agroecological analysis in agricultural sciences is currently under way throughout the world. At this juncture four main methodological approaches are routinely used:
1. **Analytic description.** Many studies are under way that carefully measure and describe agricultural systems and measure particular properties such as plant diversity, biomass accumulation, nutrient retention, and yields. For example, the International Center on Agroforestry (ICRAF) has been developing an international database on the various types of agroforestry systems, and is correlating them with a variety of environmental parameters to develop systematic regional and crop models (Nair 1984, Huxley 1983). This kind of information is valuable for expanding our understanding of the types of existing systems, which components are normally found together and in what environmental context. It is the necessary first step. Representative studies along these lines are numerous and include Ewel et al. 1984, Alcorn 1984, Marten 1986, Denevan et al. 1984, and Posey 1985.

2. **Comparative analysis.** Comparative research usually involves comparing a monoculture or other cropping system with a more complex traditional agroecosystem. Comparative studies like this involve analysis of productivities of particular crops, pest dynamics, or nutrient status as they correlate with factors like crop field diversity, weed frequencies, insect populations, and nutrient cycling patterns. Several such studies have been carried out in Latin America, Africa, and Asia (Glover and Beer 1986, Uhl and Murphy 1981, Irvine 1987, Marten 1986 and Woodmansee 1984). Such projects use standard scientific methodologies to illuminate the dynamics of particular local mixed cropping systems compared with monocultures. These data are often useful, but the heterogeneity of local systems may obscure how they are functioning.

3. **Experimental comparison.** To clarify the dynamics and reduce the number of variables many researchers develop a simplified version of an indigenous system in which the variables can be more closely controlled. For example, yields of an intercrop of corn, beans, and squash can be compared with pure stands of each of these crops.

4. **Normative agricultural systems.** These are often constructed with particular theoretical models in mind. A natural ecosystem is mimicked, or an indigenous agriculture system could be painstakingly reconstituted. This approach is being experimentally evaluated by several researchers in Costa Rica. They are developing cropping systems that emulate the successional sequences by using cultivars that are similar botanically or morphologically to plants in various successional sequences (Hart 1979, Ewel 1986).

While agronomy most certainly has been the mother discipline of agroecology/ecology, it was strongly influenced by the emergence of environmentalism and the expansion of ecological studies. Environmentalism was necessary to provide the philosophical framework on which the value of the alternative technologies and the normative project of agroecology could rest. Ecological studies were critical to expand the paradigms through
which agricultural questions could be developed, and the technical skills for analyzing them.

**Environmentalism**

*Importance of the movement.* A major intellectual contributor to agroecology has been the environmental movement of the 1960s and 1970s. As environmental issues translated into agroecology they infused parts of the agroecology discourse with a critical stance toward production oriented agronomy, and increased sensitivity to a broad range of resource issues.

The 1960s version of the environmental movement arose initially out of concern about pollution issues. These were analyzed as a function of both technology failures and population pressures. The Malthusian perspective gained particular force in the mid-1960s with works like Paul Ehrlich's *The Population Bomb* (1966) and Garrett Hardin's "Tragedy of the Commons" (1968). These authors linked environmental degradation and resource depletion primarily to population increases. This point of view was expanded technically by the publication of Donella Meadow's *The Limits to Growth* (1972) which used computer simulations of global trends in population, resource use, and pollution to generate scenarios for the future, which were generally disastrous. This position has been critiqued from methodological and epistemological perspectives (Simon and Kahn 1985).

While *The Limits to Growth* developed a generalized model of the "environmental crisis," two later seminal volumes had particular relevance to agroecological thought because they outlined visions of an alternative society. These were the "Blueprint for Survival" (*The Ecologist, 1972*) and Schumacher's *Small Is Beautiful* (1973). The works incorporated ideas about social organization, economic structure and cultural values into comprehensive, more or less utopian visions. "Blueprint for Survival" argued for decentralization, smallness of scale, and an emphasis on human activities that would involve minimal ecological disruption and maximum conservation of energy and materials. The passwords were self-sufficiency and sustainability. Schumacher's book emphasized a radical evaluation of economic rationality ("Buddhist economics"), a decentralized model of human society ("two million villages"), and appropriate technology. Of particular significance in *Small Is Beautiful* was the extension of these ideas to the Third World.

*Agricultural questions.* The environmental issues as they pertained to agriculture were clearly signaled by Rachel Carson's *Silent Spring* (1964), which raised questions about the secondary impacts of toxic substances, especially insecticides, in the environment. Part of the response to these problems was the development of pest management approaches to crop protection that were in theory and practice based entirely on ecological...
Toxicity of agrochemicals was only one of the environmental questions, since energy resource use was also becoming an increasingly important topic. The energy costs of particular production systems required evaluation, particularly early in the 1970s when oil prices skyrocketed. Pimentel's 1973 classic study showed that in U.S. agriculture, each kilocalorie of corn was "purchased" at enormous energetic cost of external energy. U.S. production systems were subsequently compared with several other forms of agriculture that were less productive per unit area (in terms of kilocalories per hectare) but much more efficient in terms of return per unit of energy expenditure. The high yields of modern agriculture are purchased at the price of numerous inputs including nonrenewable inputs like fossil fuel and phosphorous.

In the Third World, these inputs are often imported and strain the international balance of payments and debt situation of many developing countries. Further, because food crops do not receive most of these inputs, production gains may not translate into a better food supply (Crouch and de Janvry 1980, Graham 1984, Dewey 1981). Finally, the social consequences of this model have complex and often extremely negative impacts on local populations, particularly those with limited access to land and credit. These issues are discussed in more detail later in this chapter, and elsewhere in this volume.

The toxicity and resource issues in agriculture dovetailed with the larger questions of technology transfer in Third World contexts. The Careless Technology (edited by Milton and Farver in 1968) was one of the early major attempts to document the effects of development projects and the transfer of temperate-zone technologies on the ecologies and societies of developing countries. Increasingly, researchers from several fields began to comment on the poor "fit" between First World land use approaches and Third World realities. Janzen's 1973 article on tropical agroecosystems was the first widely read evaluation of why tropical agricultural systems might function differently from those of the temperate zones. This chapter and that of Levins (1973) was a challenge to agricultural researchers to rethink the ecology of tropical agriculture.

At the same time, the larger philosophical issues raised by the environmental movement resonated with the reevaluation of the goals of agricultural development in the United States and the Third World, and the technological basis on which these would be carried out. In the developed world these ideas had only moderate impact on the structure of agriculture, because the reliability and availability of agrochemical and energetic inputs to agriculture resulted in minor transformations in the patterns of resource use in agriculture. In situations where farmers and nations were constrained by resources, where regressive distributional structures prevailed, and where temperate zone approaches were often inappropriate for local environmental
conditions, the agroecology approach seemed particularly relevant. The integration of agronomy and environmentalism dovetailed in agroecology, but the intellectual foundations for such an academic mix were still relatively weak. A clearer theoretical and technical approach was needed, particularly with respect to tropical systems. The developments in ecological theory were to have particular relevance to the evolution of agroecological thought.

Ecology

Ecologists have been singularly important in the evolution of agroecological thought for several reasons. First, the conceptual framework of agroecology and its language are essentially ecological. Second, agricultural systems are themselves interesting research ensembles where researchers have much greater ability to control, test, and manipulate the components of the system compared with natural ecosystems. These can provide test conditions for a wide array of ecological hypotheses, and indeed have already contributed substantially to the body of ecological knowledge (Levins 1973, Risch et al. 1983, Altieri et al. 1983b, Uhl et al. 1988). Third, the explosion of research on tropical ecosystems has drawn attention to the ecological impacts of expanding monocultural systems in zones characterized by extraordinary diversity and complexity (Janzen 1973, Uhl 1983, Uhl and Jordan 1984, Hecht 1985). Fourth, a number of ecologists have begun to turn their attention to the ecological dynamics of traditional agricultural systems (Gliessman 1982a, 1982b, Altieri and Farrell 1984, Anderson et al. 1985, Marten 1986, Richards, P. 1985 and 1986).

Three areas have been particularly critical in the development of agroecological analyses: nutrient cycling, pest/plant interactions, and succession. Pest/plant interactions and successional issues are dealt with in more detail throughout this volume. This section will focus primarily on nutrient cycling.

In the early 1960s, nutrient cycling analysis of tropical ecosystems became a focus of interest in the tropics and as a vital ecosystem process, given the general poverty of many tropical soils. Several significant studies including Nye and Greenland's 1961 research, and later the series of articles and monographs derived from the work at San Carlos, Venezuela; Catie, Costa Rica; and other Asian and African sites has been seminal in illuminating the mechanisms of nutrient cycling in both native forests and cleared areas (Jordan 1985, Uhl and Jordan 1984, Buschbacher et al. 1988, Uhl et al. 1988).

The ecological findings of this nutrient cycling research that had the greatest impact on agricultural analysis were:
• The relationship between diversity and interspecies nutrient strategies
• The importance of structural features for enhancing nutrient capture both above and below ground
• The dynamics of physiological mechanisms for nutrient retention
• The importance of associative relations of higher plants with microorganisms such as mycorrhiza and symbiotic nitrogen fixers
• The importance of biomass as the site of nutrient storage

These findings suggest that ecological models of tropical agriculture include a diversity of species (or at least cultivars) to take advantage of the variability of nutrient uptake, both in terms of different nutrients and in capturing nutrients from different depths of the soil. The information generated by ecological studies of nutrient cycling also suggest the use of plants that readily form symbiotic associations, such as legumes, and the more widespread use of perennials in the production system, as a means of nutrient pumping from different depths of the soil and to increase the total ecosystem nutrient storage capacity. Many of these principles were already in practice in rural tropical agricultural systems.

In most ecological literature the comparison of natural ecosystems with agroecosystems has been based on agroecosystems developed by ecologists after some observation of local ecosystems, rather than truly locally evolved ones. Moreover, research questions focused on parameters like seed diversity, biomass accumulation, and nutrient storage in succession. This research has provided us with an understanding of some of the dynamics of agricultural systems as biological entities, but how management (except that carried out by relatively inexperienced graduate students) influences these processes remains an enormously unexplored area. (For a salient exception in this regard see Uhl et al. 1988).

The limitations of the purely ecological approach are being increasingly overcome as researchers begin to examine peasant and indigenous systems in multidisciplinary teams and from a more holistic perspective (Anderson and Anderson 1983, Anderson et al. 1985, Marten 1986, Denevan et al. 1984). These efforts attempt to put agriculture in a social context; they use indigenous local models (and indigenous explanations for why they do particular activities) for developing hypotheses that can then be tested using agronomic and scientific methods. This is a burgeoning research area with major theoretical and applied implications and a major inspiration to agroecological theory and practice.

**Indigenous Production Systems**

Another major influence on agroecological thought has come from the research efforts of anthropologists and geographers concerned with
describing and analyzing the agricultural practices and logic of indigenous and peasant peoples. These studies have typically been concerned with resource use and management of the entire subsistence base, not just the agricultural plot, and have focused on how this subsistence base is explained by local peoples and how social and economic change affect production systems. The scientific analysis of local knowledge has been an important force in reevaluating the assumptions of colonial and agricultural development models. The pioneer work of this type was that of Audrey Richards (1939) on the citamene swidden practices of the African Bemba. The citamene system involves using tree litter as compost in agriculture of the scrub woodlands of central Africa. This study, with its emphasis on the outcomes of agricultural technologies and ecological explanations of native people, stood in stark contrast to the derogatory perceptions of native agriculture, which viewed local practices as messy and inferior.

Another major contribution on indigenous cultivation was the seminal work by Conklin (1956), which laid the groundwork for reevaluating shifting cultivation based on ethnographic and agronomic data on the Hanunoo of the Philippines. This work pointed out the ecological complexity of shifting cultivation patterns as well as the diversity of types of shifting cultivation, and the importance of multi-cropping, rotation cropping and agroforestry systems in the overall shifting cultivation production framework. It is among the earliest and most widely known studies of the structure and complexity of shifting cultivation, and incorporates many ecological insights.

Of particular importance was Conklin's emphasis on native ecological knowledge, and the importance of tapping this rich source of scientific understanding. He emphasized, however, that access to this information would require ethnographic as well as scientific skills.

Researchers such as Richards (1985), Bremen and deWit (1983), Watts (1983), Posey (1984), Denevan et al. (1984), Brokenshaw et al. (1979), and Conklin (1956), among many others, have explored indigenous systems of production and categories of knowledge about environmental conditions and agricultural practices. This body of research focuses on the native view of production systems and analyzes them with the methods of western science. All of these authors have emphasized that social organization and the social relations of production should be considered as closely as the environment and cultivars. This emphasis on the social dimensions of production is an important basis for understanding the production logic of agricultural systems.

Another important result of much of the work on indigenous production systems is the idea that different notions of efficiency and rationality are required to understand indigenous and peasant systems. For example, efficiency of output per unit of labor investment, rather than a simple output per area ratio, is basic to the production logic of many Third World
cultivators. Practices that focus on risk aversion may not be high yielding in the short run, but may be preferable to highly productive and risky land options. Labor availability, particularly at seasonal pulses like harvesting, may also influence the types of agricultural systems that are favored.

This kind of research has been influential in developing the counter arguments to those who attributed the failure of agricultural technology transfers to ignorance and indolence. This approach, with its emphasis on the human factors in agricultural systems, also focused greater attention on the strategies of peasants of different class strata, and increasingly on the role of women in agriculture and resource management (Deere 1982, Beneria 1984, Moock 1986).

Ethnoagricultural analysis has done much to expand the conceptual and practical tool kit of agroecology. The focus on "emic" frameworks (based on a given culture's explanation) has suggested relationships that "etic" frameworks (that is, external frameworks, usually referring to western models of explanation) would not easily capture, but that can often be tested with the methods of western science. Moreover, this research has expanded the conception of what can usefully be considered agriculture, as many groups are engaged in forest ecosystem manipulation through the management of succession and actual reforestation (Posey 1985, Anderson et al. 1985, Alcorn 1984). Moreover, locally developed agriculture incorporates numbers of cultivars whose germplasm is essential to "developed" breeding programs like those of manioc and beans, and also includes numbers of plants with the potential for more widespread use in difficult environments. Finally, such work valorizes the scientific achievements of hundreds of years of plant breeding and agronomic work by local peoples.

The study of indigenous agricultural systems has provided much of the raw material for the development of hypotheses and alternative production systems for agroecology. Native agriculture is now increasingly studied by multidisciplinary teams to document practices, and classification categories have been developed to analyze the biological processes within agricultural systems and to evaluate aspects of the social forces that influence agriculture. The study of indigenous systems has been seminal in the development of agroecological thought.

Development Studies

The study of rural Third World development has also made a major contribution to the evolution of agroecological thought. Rural analysis has helped clarify the logic of local production strategies in communities undergoing intense transformation, as rural areas increasingly are integrated into larger regional, national, and global economies. Rural development studies have documented the relations between socioeconomic factors and
the structure and social organization of agriculture. Several themes in development research have been particularly important in agroecology, including the impacts of externally induced technology and cropping change, the effects of market expansion, the implications of changes in social relations, and the transformation in tenure structures and access to customary resources. All of these processes are deeply interwoven. How they affect regional agroecosystems is a result of complex historical and political processes.

Research on the Green Revolution was important in the evolution of agroecological thought because studies of the impact of this technology were instrumental in illuminating the types of biases that predominated in agricultural and development thinking. This research also resulted in the first really multidisciplinary analysis of ecological, social, and economic tenure issues and technical change in agriculture by a broad spectrum of analysts. The extraordinary acceleration in peasant social stratification associated with the Green Revolution indicated immediately that this was not a scale-neutral technology, but one that could dramatically transform the basis of rural life for large numbers of people.

As noted in Perelman 1977, the major beneficiaries of such technologies were urban consumers. The Green Revolution strategy evolved when the problems of poverty and hunger were viewed primarily as problems of production. This diagnosis implied several strategies that focused on the areas where production gains could be realized rapidly: better quality soils and irrigated lands among farmers with substantial assets. In terms of raising output, it succeeded; at bottom it was part of a policy of betting consciously on the strong (Chambers and Ghildyal 1985, Pearce 1980). It is now generally recognized that aggregate increases in food production alone will not overcome rural starvation and poverty, although it may reduce some urban food costs (Sen 1981, Watts 1983).

The Green Revolution had consequences in rural areas that often served to marginalize much of the rural population. First, it focused its benefits on the already resource-rich farmers, accelerating the differentiation between them and other rural inhabitants, so rural inequality often increased. Second, it undermined many forms of access to land and resources such as share cropping, labor tenancies, and access to water supplies and grazing lands. This reduced the diversity of subsistence strategies available to rural households and thus increased their dependence on the agricultural plot. With the narrowing of the genetic basis of agriculture, risk increased because crops became more vulnerable to pest or disease outbreaks and the vagaries of climate. In irrigated rice, the secondary pollution generated by the increased use of pesticides and herbicides often undermined the important source of local protein: fish.

The analysis of the Green Revolution from several disciplines constituted
the first holistic view of agricultural/rural development strategies. It was the first widely publicized evaluation that incorporated ecological, technological, and social critiques. This kind of approach and analysis has been the prototype for several subsequent agroecological studies, and the progenitor of farming systems research.

It is now well recognized that Green Revolution technologies can be applied in limited areas, and there have been calls by several rural development analysts to redirect agricultural research toward resource-poor farmers. Worldwide there are more than one billion such farmers with very limited assets, income, and production flows who work in an agricultural context of extreme marginality. Agricultural approaches emphasizing technological packages have generally required resources to which most of the world's farmers have no access (Table 1.1).

Many rural development analysts had recognized the limitations of large-scale and Green Revolution-oriented approaches to rural development, but these agricultural models have overwhelmingly dominated agricultural development projects in much of the Third World. While research station results looked extremely promising, the weak replicability of these results in the field has caused serious difficulty in many projects. The transfer of technology approach tended to accelerate differentiation, exacerbating many difficult political situations, or the technologies were partially adopted and in many cases they were not adopted at all (Scott 1978 and 1986).

Several explanations accounted for the poor transfer of technology, including the idea that farmers were ignorant and needed to be taught how to farm. Another set of explanations focused on farm level constraints such as lack of credit that limited the ability of farmers to adopt technologies. In the first case the farmer is viewed as basically at fault. In the second, infrastructural questions of various types are considered the culprit. Never was the technology itself criticized.

Many field researchers and development practitioners have been frustrated by these explanations and have increasingly indicated that the technologies themselves require substantial re-evaluation. They have argued that the farmer's decision to adopt a technology is the true test of its quality. This approach has often been called "the farmer first and last," or "farmer back to farmer," or "indigenous agricultural revolution." As Rhoades and Booth (1982) put it, "The basic philosophy upon which the model is based is that agricultural research and development must begin and end with the farmer. Applied agricultural research cannot begin in isolation out on the research station or with a planning committee out of touch with farm conditions. In practice, this means obtaining information about and understanding the farmers' perception of the problem, and accepting farmers' evaluation of the solution." This approach calls for much broader farmer participation in the design and implementation of rural development programs (Chambers...
TABLE 1.1 The contrast in physical and socioeconomic conditions of resource-rich vs. resource-poor farmers (modified from Chambers and Ghildyal 1985).

<table>
<thead>
<tr>
<th></th>
<th>Research Station</th>
<th>Resource Rich Farmers (RRF)</th>
<th>Resource Poor Farmers (RPF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography</td>
<td>flat or terraces</td>
<td>flat or terraces</td>
<td>undulated or sloped</td>
</tr>
<tr>
<td>Soils</td>
<td>deep, few</td>
<td>deep, few</td>
<td>shallow, infertile,</td>
</tr>
<tr>
<td></td>
<td>constraints</td>
<td>constraints</td>
<td>serious constraints</td>
</tr>
<tr>
<td>Nutrient deficiency</td>
<td>rare, remedial</td>
<td>occasional</td>
<td>quite common</td>
</tr>
<tr>
<td>Hazards (fire, landslides, etc.)</td>
<td>few</td>
<td>few controllable</td>
<td>common</td>
</tr>
<tr>
<td>Irrigation</td>
<td>often, full control</td>
<td>usually available,</td>
<td>rare, unreliable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>reliable control</td>
<td></td>
</tr>
<tr>
<td>Size of unit</td>
<td>large, contiguous</td>
<td>large or medium,</td>
<td>small, irregular,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>contiguous</td>
<td>often non-contiguous</td>
</tr>
<tr>
<td>Disease, Pests, Weeds</td>
<td>controlled with</td>
<td>controlled with</td>
<td>crops vulnerable</td>
</tr>
<tr>
<td></td>
<td>chemicals, labor</td>
<td>chemicals, labor</td>
<td>to infestation</td>
</tr>
<tr>
<td>Access to fertilizers,</td>
<td>unlimited,</td>
<td>high, reliable</td>
<td>low, unreliable</td>
</tr>
<tr>
<td>improved seed, etc.</td>
<td>reliable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seeds</td>
<td>high quality</td>
<td>high quality</td>
<td>own seed</td>
</tr>
<tr>
<td>Credit</td>
<td>unlimited</td>
<td>good access</td>
<td>poor access with</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>seasonal shortages</td>
</tr>
<tr>
<td>Labor</td>
<td>no constraint</td>
<td>controlled by</td>
<td>family,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>farmer, hired</td>
<td>constraining at</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>seasonal peaks</td>
</tr>
<tr>
<td>Prices</td>
<td>irrelevant</td>
<td>lower for inputs,</td>
<td>higher for inputs,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>higher for outputs</td>
<td>lower for outputs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>relative to RPF</td>
<td>relative to RRF</td>
</tr>
<tr>
<td>Priority for food production</td>
<td></td>
<td>low</td>
<td>high</td>
</tr>
</tbody>
</table>


One consequence of this stance has been the recognition of the very extensive knowledge of farmers in entomology, botany, soils, and agronomy, which can serve as the starting point for research. Here again, agroecology
has been identified as a valuable analytical tool as well as a normative approach to research.

Agroecology fits well with the technological issues requiring more environmentally sensitive agriculture practices, and often finds congruencies in both environmental and participatory development in philosophical perspectives. The diversity of concerns and bodies of thought that have influenced the development of agroecology is broad indeed. However, this is the range of issues that impinges on agriculture. It is for this reason that we now see agroecologists with much richer training than is usual for students of agricultural sciences and many more multi-disciplinary teams dealing with these issues in the field. While it is a discipline in its infancy, and so far has raised more questions than solutions, it has widened the agricultural discourse.
The Methodology and Practice of Agroecology

Richard B. Norgaard and Thomas O. Sikor

The methodology and practice of agroecology stem from different philosophical roots than those of conventional agricultural science. To have different roots is to be radical in the true sense of the word. This chapter addresses how these differences in philosophical roots affect the methodologies, the organization, and the social and environmental consequences of both conventional agriculture and agroecology. Agroecology considers both the agroecological and social system in which farmers work, it puts relatively little emphasis on laboratory and experiment station research and gives considerably more emphasis to on-farm experiments, and it is more open to participation in the research process by farmers themselves. The development of conventional agriculture in Latin America and the role of non-governmental organizations (NGOs) in the dissemination of agroecology are elaborated to illustrate these differences.

The Importance of Philosophical Premises

Conventional agricultural scientists follow the dominant premises of modern science (Norgaard 1994). For example, they assume that farm production can be understood objectively, apart from farmers, how farmers think, and apart from social systems and from the surrounding agroecosystem. Accordingly, they conduct controlled experiments in laboratories and on the plots of experimental field stations. Furthermore, they assume that farming can be understood atomistically, or in small parts. Hence they divide themselves into disciplines and subdisciplines and study the physical
properties of soil apart from biological properties and apart from the life the soil supports. They examine the toxicity to insects of different chemicals without considering how diverse insects interact with each other and with plants. And the separate understandings are developed into separate technologies for plant nutrition and insect control. Then they assume these findings can be transferred to farmers in the form of new technologies. Needless to say, farmers have not always found that the new technologies fit their farming system. Furthermore, the separately and individually derived technologies frequently have unexpected effects when used on a farm, especially when used in combination. And the cumulative effects of conventional agricultural technologies when used by all farmers together sometimes have devastating ecological and economic impacts.

Conventional agricultural scientists have long realized that their agricultural technologies have problems. Extension services were established, which employed special agents to extend the technologies to the farmers, in order to bridge the gap between scientists and farmers. Later, conventional agricultural scientists tried to design integrated packages of technologies which fit together. Still later, they began to pay more attention to farmers' needs, tried to listen to the farmers, and began to conduct on-farm research. Conventional agricultural scientists, however, have only been moderately successful in overcoming the problems of their technologies, because they have yet to realize that the problems are inherent to the philosophical premises of their methods and practices. For example, they have not really been able to listen to what farmers have to say because the philosophical premises of conventional science do not give farmers' ways of learning and knowing any legitimacy.

The dominant premises of modern science and some alternative premises are listed in Table 2.1. *Atomism* posits that parts can be understood apart from the systems in which they are embedded and that systems are simply the sum of their parts. *Mechanism* posits that relations between parts of a system do not change, a necessary condition for prediction and control. *Universalism* posits that the heterogeneous and complex world around us can be explained by the interaction of a relatively small number of universal principles. *Objectivism* posits that our values, ways of knowing, and actions can be kept apart from the systems we are trying to understand. *Monism* posits that our separate disciplinary ways of knowing are merging into a coherent whole. Conventional agricultural science adopted these premises in the 19th century, and it remains organized around them today. In fact, these "isms" poorly characterize how individual agricultural scientists actually think about the complexities around them. They are, however, the official assumptions, the ones reinforced by explanations of how agricultural science is supposed to work. They are the suppositions which structure modern agricultural education, research, and extension organizations.
## TABLE 2.1 Dominant premises of modern science and alternatives.

<table>
<thead>
<tr>
<th>Dominant Premises</th>
<th>Alternate Premises</th>
</tr>
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<tbody>
<tr>
<td><strong>ATOMISM:</strong> Systems consist of unchanging parts and are simply the sum of their parts.</td>
<td><strong>HOLISM:</strong> Parts cannot be understood apart from their wholes and wholes are different from the sum of their parts. Parts might evolve new characteristics or totally new parts can arise.</td>
</tr>
<tr>
<td><strong>MECHANISM:</strong> Relationships between parts are fixed, systems move smoothly from one equilibrium to another, and changes are reversible.</td>
<td>Systems might be mechanical, but they might also be deterministic yet not predictable or smooth because they are chaotic or simply very discontinuous. Systems can also be evolutionary.</td>
</tr>
<tr>
<td><strong>UNIVERSALISM:</strong> Diverse, complex phenomena are the result of underlying universal principles which are few in number and unchanging over time and space.</td>
<td><strong>CONTEXTUALISM:</strong> Phenomena are contingent upon a large number of factors particular to the time and place. Similar phenomena might well occur in different times and places due to widely different factors.</td>
</tr>
<tr>
<td><strong>OBJECTIVISM:</strong> We can stand apart from what we are trying to understand.</td>
<td><strong>SUBJECTIVISM:</strong> Social and most &quot;natural&quot; systems cannot be understood apart from our activities, our values, and how we have understood and hence acted upon these systems in the past.</td>
</tr>
<tr>
<td><strong>MONISM:</strong> Our separate individual ways of understanding complex systems are merging into a coherent whole.</td>
<td><strong>PLURALISM:</strong> Complex systems can only be known through multiple, different patterns of thinking, each of which is necessarily a simplification of reality. Different patterns are inherently incongruent.</td>
</tr>
</tbody>
</table>

Consequently, even when an individual agricultural scientist has comprehended agricultural problems from another philosophical perspective, his or her findings must be communicated and implemented within modern agricultural institutions using the dominant paradigm, and the new insights are lost.

The alternate premises of Table 2.1 contrast as sharply as possible with the dominant premises. Their differences sharpen our understanding of the
dominant position. But the alternate premises listed are merely illustrative for there are many possible alternatives and combinations.

The five dominant isms are perfectly good suppositions from which to reason. They have facilitated a level of prediction and control beyond that known before. The prediction and control of science following the dominant isms has proven to be more limited, systemically and temporally, than has been believed by conventional scientists. These limitations are at the root of the unexpected consequences, the problems which occur to other parts of the agroecosystem, off the farm, and in later years. Had modern agricultural technologies and institutions not been based too solely on these premises, had other patterns of understanding been given equal respect, the long-term and systemic consequences for people and for agroecosystems might have been foreseen, ameliorated, or avoided. The problems of conventional agriculture result from the dominance of these isms.

Neither conventional agricultural scientists nor agroecologists are typically conscious of the philosophical premises underlying their research or how philosophy structures the organizations through which they work. Nevertheless, when the methodological issues are raised, agroecologists are more likely to be comfortable with the alternate suppositions of Table 2.1 and are more likely to be critical of several of the dominant premises. At the same time, many agroecologists also reason and sometimes conduct research within the dominant mode. Indeed, some people who think of themselves as agroecologists solely conduct research in the dominant mode but cooperate with others who try to utilize their understandings in alternative modes. Thus the difference between conventional agricultural scientists and agroecologists is that agroecologists as a whole tend to be more methodologically pluralistic.

Curiously, the alternate premises are the more intuitive, closer to our "common sense." At the same time, following the alternate suppositions, one discovers that answers are going to be multiple and less clear. This means that logical thinking per se will not inform us of what should be done, because the multiple logics supported by alternative starting points give different insights. Science only provides unique answers when scientists are all using the same premises. Methodological pluralism requires that non-scientific means of weighing multiple insights must be invoked. Such judgment is best left to collective decisionmaking by the communities most affected.

Agroecologists are more likely to take a systems perspective. Indeed, some researchers think of agroecology as simply an ecosystems approach to agriculture. It is important to keep in mind that many agroecologists are as concerned with the social system as with the environmental system in which the farmer is operating. And ultimately, it is the interaction of the two systems which must be viable and beneficial for people.
A Coevolutionary Perspective of Development

The framework illustrated in Figure 2.1 has been found to be especially beneficial for understanding systems interaction. Think of development as a coevolutionary process between the social system and environmental system. Furthermore, think of the social system as being made up of systems of knowledge, values, technology, and organization. Each of these systems is related to each of the others in that each exerts selective pressure on the evolution of each of the others. Through selective pressure on each other, they all coevolve together. For example, within the knowledge system, deliberate innovations, chance discoveries, and random experiments take place. Whether these new additions of knowledge prove fit and are retained or not depends on the selective influences of values, organization, technology, and the environment. With each system putting selective pressure on each of the others, they all coevolve to reflect each other. Thus everything is coupled, yet everything is constantly changing.

Coevolutionary agricultural development has been taking place for millennia. The rise of paddy rice culture in Southeast Asia is an instructive example. The land-extensive practice of slash and burn agriculture was gradually abandoned as investments were made in dikes, terraces, and water delivery systems over a period of centuries. The benefits from the ecological transformation to paddy culture came in the form of superior weed control and greater nutrient retention. The transformation, however, was not unilateral. The social system also evolved in order to maintain the environmental transformation. Social mechanisms reinforcing individual behavior which supported the environmental transformation selectively evolved. In short, the maintenance and continuation of the environmental transformation was sustained by complex social organization for water management.

FIGURE 2.1 The coevolution of knowledge, values, social organization, technology, and the biological system.
rights to land, and labor exchanges; the social and environmental systems coevolved together, each reflecting the other. Similarly, new technologies, new values, and new ways of knowing were selected for in light of the coevolution between the environment and social organization. Farming systems, from slash and burn in the tropical forests to the modern, energy-intensive systems in temperate regions, can be understood as coevolved systems.

The coevolutionary perspective highlights agricultural systems as integral systems. It also emphasizes that traditional agricultural systems are not stagnant. They have been evolving, and sometimes improving, over millennia. The coevolutionary perspective puts people and how people think inside of the process. It shows, for example, how modern agroecosystems reflect conventional scientific premises. The pests of modern agriculture have coevolved with the pesticides that have been applied on the premise that pests could be thought of apart from the system as a whole.

One of the most important features of the coevolutionary perspective is that it gives legitimacy to the cultural and experiential knowledge of farmers. Their ways of understanding may not translate into scientific ways of understanding, but how and what they understand has proven fit within their system and can be used to help understand that system. With a coevolutionary perspective in mind, agroecologists can overcome the subtle indoctrination they themselves received as students about the superiority of conventional science, feel genuine respect for the knowledge of farmers, blend their ways of knowing with new ways of knowing, and work effectively together. The perspective provides a strong philosophical basis for participatory research, for the incorporation of farmers in the research process, a technique increasingly being used by agroecologists.

While conventional agricultural scientists have tried to design whole farming systems, the coevolutionary perspective stresses how the adoption of farming technologies is a matter of selection for their fitness with other systems. One can design better agricultural technologies if one is aware of how they might interact with other systems, but the complexities of such interactions suggest that scientists might better think of themselves as experimenters who might affect and accelerate the coevolutionary process by introducing multiple mutations, only some of which will prove fit. "Tinkerers" in a coevolving world are more effective than grand designers. Social and environmental systems are constantly coevolving, but the direction of coevolutionary change may not always be beneficial for people or the environment of people in the future.

The pattern of coevolution might significantly change, for example, through:

1. An exogenous change in the ecosystem
2. New knowledge about how to interact with an ecosystem
3. A subsidy from (or the removal of a transfer to) another region
4. A redistribution of power in the social system

The coevolutionary perspective certainly does not give us the illusion that we have the power to design our future. But we are part of the process. It does indicate that by being aware of the process of change, we can more effectively intervene in it to facilitate coevolutionary changes which favor people and environmental sustainability.

A Coevolutionary Interpretation of Conventional Agricultural Development in Latin America

Agricultural modernization in Latin America through conventional technologies has brought increases in farm productivity and in foreign currency earnings. Those producers whose land and socioeconomic position were compatible with conventional agricultural technologies have fully been integrated into a market economy. But modernization has also been a culturally, ecologically, and socially disruptive process. In the name of progress, agroecosystems have been transformed, traditional cultures distorted, and social structures fundamentally changed. Peasants without sufficient access to land and other productive resources did not fit the ecological and socioeconomic conditions of conventional agriculture and remained outside the dynamics of rural development. The number of peasants increased in Latin America by 43.6% between 1950 and 1980 (de Janvry et al. 1989). Around 1980, approximately 22.5% of the Latin American population belonged to the rural poor. This corresponded to an average of two-thirds of the rural population being poor for the whole continent and up to 85% for some countries (FAO 1988). Around 40% of the rural population was not even able to cover basic food needs.

The Latin American food sector has become highly dependent on imports of agricultural products, inputs, and machinery for food processing (de Janvry et al. 1988, FAO 1988, Redclift and Goodman 1991). Most countries, even those which provide good geographical and climatic conditions for agriculture, have to import part of their food requirements for cereals and basic foodstuffs. Food distribution has been highly uneven, as indicated by a high incidence of malnutrition of up to 40% of the population in the cases of Peru, Honduras, and Guatemala. The instability in food production and consumption have increased in recent years. Although the number of peasants has increased for all Latin America, their share of total agricultural production has been decreasing. Still, it is estimated that 41% of all products originate on peasant family and subfamily farms.

Modernization has also entailed massive environmental damage (FAO 1988, LACDE 1990). Colonization, extraction, and agricultural production
activities have created massive perturbations and transformation, especially in the tropical forests. Overexploitation of natural resources due to poverty and abandonment of traditional agricultural practices and massive transformation of the environment in the areas of recent colonization have caused erosion, loss in soil fertility, and downstream sedimentation. Genetic resources have been eroded, comprising (1) primitive cultivars and adapted breeds of animals, which evolved as part of traditional cultures over centuries, (2) unmanipulated wild plant and animal species, and (3) wild progenitors and relatives of domestic plants and animals used today. Fertilizers, insecticides, pesticides, and herbicides have been over- and/or inadequately utilized, bearing direct effects on human health through toxicity and more indirect consequences through ecological damage. In many cases, environmental destruction and rural poverty are tightly connected as a two-way process: on the one hand, poor people are forced to overexploit their resource base due to economic pressure. On the other, peasants, who are pushed to or live in marginal environments are constrained by the limited productivity of their resource base.

Modernization has not reached resource-poor farmers in Latin America. It has increased agricultural productivity and overall production but also led to significant environmental and social consequences in many regions. Modernization has not succeeded in improving peasant agriculture because it has relied on technologies that displace nature and increased the distances between social and ecological processes.

Conventional agricultural practices displace nature. Maintenance needs shift from the ecosystem to the social system. Industrial produced fertilizer substitutes for relationships between plants and nitrogen-fixing bacteria, overriding rather than working with agroecosystems. Pesticides and insecticides replace equilibrating mechanisms such as pest and insect predators. More and more complex institutional arrangements, for example insurance and future markets, substitute for ecologically based methods of risk management. The relative importance of agroecosystem properties changes from farming systems which tend to be productive and stable and yet retain a high degree of sustainability to farming systems characterized by high productivity but lower sustainability and stability. Agricultural research in Latin America has placed its focus on agriculture in temperate zones and on flat land with soils characterized by a high buffering capacity (de Janvry and Dethier 1985, Piñeiro and Trigo 1983). The research has been organized according to specific crops and agricultural components, and has produced simple agricultural packages that are suitable only for uniform, controlled environments, that ignore work against ecological processes.

Modern agricultural practices also increase the distances between social and ecological processes. Conventional agricultural development has made the linkages between producers and consumers, planners and beneficiaries,
researchers and practitioners more indirect and longer, a process which is most simply and effectively understood as "distancing." Modern agricultural decisions are based on signals transmitted through factor, product, and capital markets. Production increases are supported by subsidies from far-away regions, mostly through fossil hydrocarbons. Risk management shifts from individual producers to traders in regional and global markets, reducing over-all risk to consumers, but increasing the vulnerability of individual producers. Conventional modern technologies are very science-intensive, and agricultural knowledge is generated by specialized experts, who conduct research in controlled experiments at centralized experimental laboratories and research stations. Research centralization in international and national research centers has ignored the diversity of local environments. It has also made research agendas very susceptible to external political pressures, instead of incorporating feedback mechanisms from extensionists and farmers into the research process (Piteiro and Trigo 1983, de Janvry and Dethier 1985).

Agricultural and rural development efforts have been planned in urban centers. Most recently, externally directed rural development programs took the form of Integrated Rural Development (IRD) programs. IRD programs were motivated by the apparent failure of previous development efforts in attacking problems of rural poverty isolated from their social context (Lacroix 1985, FAO 1988, Martinez 1990). Institutional complexity and the costs of facilitating rural development increased. Yet, IRD programs could not overcome the deficiencies of development efforts guided by distant forces. The agencies failed in the implementation of centrally conceived plans and were unable to reach the poorest members of society. Concentration on technical components led them to neglect the human development component. They also lacked important long-term perspectives in problem-solving activities and were ineffective in building problem-solving capacity among the rural poor.

To summarize, modern agriculture entails increased distancing between producers and consumers, planners and beneficiaries, researchers and practitioners. Agricultural practices displace rather than work with processes in the ecological system. The social system thus has to invest in and maintain increasingly complex and global institutional mechanisms to regulate its interactions with the ecological system. Under the selective pressure of conventional modern agricultural practices, agroecosystems and agricultural strategies which were unique to particular cultures and ecosystems merged in the process of globalization. This development path has proven very successful in industrialized countries and for resource-rich Third World farmers in temperate zones. The modernization of agriculture through conventional technologies, however, has not promoted development for most farmers in Latin America.
Latin America's rural poor live in very heterogeneous circumstances. Local ecological settings span almost all 103 Life Zones identified by Holdridge (FAO 1988). The indigenous population, which consists of hundreds of ethnic groups, accounts for huge parts of the peasantry in many countries. In addition, modernization affected rural livelihood in different ways, transforming and differentiating the traditional peasant sector.

Local environments in Latin America show significant variations (Table 2.2). Each environment poses different stresses on agricultural production and opens different opportunities for local farmers to exploit natural fertility. In most countries, the lands without major restrictions for modern agriculture, those lands which have a growing period of more than nine months and no soil fertility or physical limitations, are scarce. The rural poor are often pushed onto marginal and fragile lands, such as steep slopes (de Janvry and Garcia 1988, FAO 1988). Marginal lands are lands which have significant environmental constraints and/or low productivity if managed with conventional agricultural practices. Fragile lands are lands that suffer significant deterioration if not cultivated following appropriate principles (Denevan and Padoch 1987).

The diversity in ecological constraints and opportunities for development has translated into various, very differentiated resource use systems embedded in diverse cultures. There are more than 460 ethnic groups in Latin America (FAO 1988). Bolivia (95%), Peru (73.1%), Guatemala (81.3%), Ecuador (58.4%), and Mexico (36%) show a high presence of indigenous groups in the rural areas. In numerous case studies, western researchers have documented indigenous slope, soil, pest, and vegetation management systems by which traditional people have made effective and efficient use of heterogeneous local ecosystems (Altieri and Hecht 1989, Browder 1989, Gliessman 1990). Their testimony demonstrates the unique ability of many indigenous groups in harsh environments to design sustainable livelihood strategies in a century-long trial and error process. Since their agricultural systems are tightly intertwined with social organization, values, the environment, and technology, pressures on those components pose dramatic threats to the survival of indigenous populations and their agricultural strategies.

Modernization has increased differences between people, resulting in increased heterogeneity in peasant livelihood strategies. Land and other productive inputs have been unevenly distributed and degrees of market integration and the availability of off-farm employment vary across regions (de Janvry et al. 1988, FAO 1988). Two main groups can be identified among the rural poor according to their access to land (FAO 1988): (1) small farmers, Minifundistas, operate holdings based on family work and only occasionally seek employment opportunities off their own farm. Minifundia comprise
half the farms in Latin American agriculture and 42% of the rural population on average; (2) landless laborers have limited or no access to land and derive their income from sources other than their own plot. The number of landless peasants is steadily increasing (de Janvry et al. 1989). In addition, differences in age and gender further diversify household survival strategies. Women's participation in the economically active rural population has increased considerably in recent years (FAO 1988). Between 15 and 30% of rural households are headed by women. Age is important since young men and women between 15 and 24 years of age often do not find employment opportunities in the rural areas.

Ecological, cultural, and socioeconomic diversity is reflected in heterogeneous livelihood strategies employed by the rural poor. To accommodate the heterogeneity, any approach to rural development in Latin America needs to integrate flexible technological and organizational strategies for meeting the needs of the rural poor. Yet not only is the Latin American peasantry very heterogeneous, it has also been marginalized by modernization.

Peasants suffer from economic, political, cultural and ecological marginalization. Agricultural policies, prices, and government services favor large-scale producers. Peasant interests are not adequately represented in the political process. Ethnic and linguistic barriers prevent the access of the

<table>
<thead>
<tr>
<th>Agricultural Environment</th>
<th>Proportion of Total Agricultural Land</th>
<th>Major Ecological Stress Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid Tropics</td>
<td>34.4%</td>
<td>Frequent acid, low fertile soils; high incidence of insects and plant diseases</td>
</tr>
<tr>
<td>Sub-humid tropics and sub-tropics with acid soils</td>
<td>10.8%</td>
<td>Low soil fertility; low retention of nutrients in soil</td>
</tr>
<tr>
<td>Semi-arid tropics and sub-tropics</td>
<td>13.9%</td>
<td>Water shortage; variable drought periods</td>
</tr>
<tr>
<td>Wetlands</td>
<td>11.5%</td>
<td>Poor drainage effects</td>
</tr>
<tr>
<td>Steep lands</td>
<td>18.4%</td>
<td>Erosion; rainfall, temperature, and soil fertility problems</td>
</tr>
<tr>
<td>Lands with no major limitations</td>
<td>3.4%</td>
<td></td>
</tr>
</tbody>
</table>

Source: FAO (1988)
indigenous population to the social system which is dominated by the foreign Mestizo culture. Small farmers have also increasingly been driven onto fragile lands with major limitations for agricultural production.

Permanent socioeconomic and institutional biases against the rural poor attest to their political and economic marginalization during the last decades (de Janvry et al. 1988, FAO 1988). In the 1960s and 1970s, during industrialization, "cheap food" policies were implemented to subsidize urban-based development. The rural population mainly served as a large reserve of cheap labor for urban-based industrial development. Policies aimed at increasing production of agricultural products were biased toward owners of large- and medium-scale farms. During the 1980s, trends in increased land concentration and declining average size of small farms have continued to prevail. Differential access to credits, production and input subsidies, support prices, input delivery systems, and public goods provided by the government (infrastructure, irrigation, etc.) has intensified the existing dichotomy in the agrarian structure. At the end of the 1980s, although comprising half the productive units in Latin American agriculture and 42% of the rural population on average, minifundia occupied only 3% of total agricultural land. In Latin American development, the peasantry has thus functioned as a "large refuge sector that symptomizes the developmental failures of the rest of the economy" (de Janvry et al. 1989).

In Latin America, as in other parts of the world, modernization has been associated with urban centers and industry, and backwardness with rural-agrarian society, particularly indigenous populations. National legal institutions have been an extremely effective marginalization mechanism by enforcing the predominance of urban norms and interests (FAO 1988). The indigenous population suffers from a double discrimination as rural poor and as a culture which is alien to the predominant one. The most visible barrier for integration is language. Indigenous people's knowledge has not been recognized as valid by the dominant western scientific paradigm. High poverty rates and alarming indicators of low living standards prevail in the regions where indigenous groups are concentrated (FAO 1988). The establishment and enforcement of reserved areas is still seen as the best way to shield indigenous cultures and agroecosystems from the destructive forces of modern society in which there is no space for them (LACDE 1990).

Economic, political, and cultural marginalization often goes hand in hand with the ecological marginalization of the rural poor, who are pushed to fragile and marginal lands (FAO 1988, de Janvry and Garcia 1988). For those people, poverty and environmental degradation feed into each other in a feedback process. In many areas, resource-poor farmers abandon traditional practices for sustainable agricultural use because those are discouraged by the commercialization of agricultural production and the domination of modern agricultural techniques. They lose the knowledge and resource base
which sustained agricultural production over centuries. Poor people are also often pushed to areas which are ecologically unsuitable for cultivation or extremely fragile, such as arid zones or regions with steeply sloping lands. Due to economic pressure to overuse the resource base, these peasants get caught in a vicious cycle of ecological damage in the environment which supports them. While acting rationally with respect to changes in their socioeconomic and/or physical circumstances, their actions inhibit their own long-term reproduction.

Marginalization implies two important features of the rural sector in Latin America. First, peasants are resource-poor farmers not only in an ecological sense, but also socioeconomically: Their livelihood is supported by very few economic, political, and cultural resources. Ecological or socioeconomic buffers protecting peasant livelihood from perturbations caused by changes in their ecological and social environment are weak. Second, external, distant forces heavily impact on and distort the local coevolution between ecosystem and social system since peasants are excluded from true participation in the economic, social, and cultural processes affecting them.

**The Rise of Agroecological NGOs**

The deficiencies of conventional agricultural development strategies demand a broader approach to rural development. NGOs in Latin America developed ideologically centered around an ecological understanding of agricultural systems (Table 2.3). Though formal evaluations are lacking in many projects, there is strong evidence that the NGOs have generated and adapted technological innovations that significantly contribute to improving peasant livelihood (Altieri 1992, Thiele et al. 1993, Bebbington and Thiele 1993). The NGOs' technological agenda has often been constrained by the lack of technical expertise, forcing them to seek the help of other NGOs or public sector agencies or leading to project failures. Yet agroecological projects have increased peasants' food security, strengthened subsistence production, generated income sources, and improved the natural resource base. They have achieved these successes with the help of innovative institutional structures and novel methodologies for working with rural communities.

Agroecological NGOs have developed an approach to technology generation and dissemination that generates new knowledge and helps adapt technical information to peasant livelihood strategies. The NGOs' goals in research and development programs include:

1. Improvement of basic food production
2. Efficient use of local resources and reduction of external inputs
3. The rescue and re-evaluation of indigenous agricultural systems
TABLE 2.3 Four examples of agroecological NGO activities in Latin America.

_Preservation of Traditional Cotton Production Systems in Brazil:_ The Brazilian Centro de Tecnologias Alternativas de Ouricouri (CTAO) began by identifying a farming system which proved to be resilient, without the utilization of pesticides, to mild levels of a widespread insect pest. CTAO has determined the reasons for this resilience by surveying 73 farmers and is currently developing low-input farming systems based on principles of biological control for areas with higher, economically damaging levels in insect incidence. Twenty farmers collaborate as co-researchers in on-farm experiments (AS-PTA/CTAO 1992).

_Vegetable Production in Bolivian Highlands:_ The Centro de Servicios Multiples de Tecnologias Apropiadas (SEMTA) promotes small-scale vegetable production in protected beds. This system was developed by SEMTA to cope with the harsh environmental constraints on vegetable cultivation in the highlands (low temperatures, seasonal water scarcity, soils of low fertility). Using only locally available resources, they manage to grow vegetables all year long. SEMTA's dissemination strategy rests on community centers which serve training, demonstration, and research purposes (SEMTA 1992).

_Consumption-Oriented Programs for the Landless:_ The Chilean Centro de Educacion y Tecnologia (CET) developed gardening techniques for rural and semi-rural dwellers with only small pieces of land adjacent to their houses to reduce their food expenditures and improve living standards. CET started with improvements to local diets through organic gardening, solar driers, earthen ovens, bee keeping, and poultry raising. Later on, the NGO included other components of the livelihood system such as the improvement of wells and housing through handicraft pumps and do-it-yourself programs.

_Regional Institution-Building:_ The Latin American Consortium on Agroecology and Development (CLADES) unites eleven NGOs which apply agroecological methods in rural development. Most member institutions operate on the basis of a bottom-up approach, using concepts and methods developed by practitioners of the popular education school. CLADES's own structure reflects the bottom-up character of agroecology by emphasizing autonomy and controlled competition among its member institutions. The regional NGO network thus demonstrates a strategy for scaling-up individual NGO efforts by emphasizing institutional specificity (technical training, dissemination of agroecological experience) and technological principles instead of technological packages (Altieri and Yurjevic 1989).

4. Increases in crop and animal diversity
5. Improvement of the natural resource base (Altieri and Yurjevic 1991)

The NGOs usually follow an integrated approach combining technology development and dissemination with other activities aimed at tackling other factors that constrain the improvement of peasant livelihood.
For example, they might provide credit, attempt to strengthen peasants’ organizational capacities, explore marketing opportunities, and deliver preventive health care services.

From an institutional perspective, the agroecological NGOs function as intermediary institutions that forge links between the peasantry, on the one side, and governments and international donors, on the other. Although some NGOs work on developing improved farming systems for commercial production, most NGOs provide services to poor subsistence farmers, who live in very heterogeneous socioeconomic and ecological circumstances. They have been guided by an explicit commitment to participation and empowerment of the rural poor. The NGOs often see agroecology, their technological agenda, and participation, their organizational agenda, as tightly interconnected, leading to a self-sustained development process based upon peasants' own technical and organizational capacity. In their work at the grassroots level, they have experimented with novel methodologies for participatory agricultural research and development, combining applied research on research stations, on-farm research, and technology diffusion. Their closeness to beneficiaries has allowed them to be responsive to the needs of the rural poor. Employing increasing numbers of university educated professionals, they often built up the capacity to conduct applied agricultural research and/or work in various regions of their countries.

The NGOs promote their agroecological agenda in multiple ways. In addition to administering independent agricultural research and rural development projects, agroecological NGOs disseminate their technologies to other NGOs and government extension agencies. For example, some NGOs train staff from government agencies and other NGOs and paratechnicians from rural communities, which are not directly included in their development program, in agroecological methods. In some countries, the NGOs have become quite powerful institutions and attempt to advocate for changes in government policies on national, regional, and local levels. They also work toward influencing the research agenda of national and international agricultural research systems, funding priorities of international donors, and curricula of universities. For these and other purposes such as technical training and coordination of research efforts, they have founded national networks, such as the Colina Agreement in Chile, and the Latin American Consortium on Agroecology and Development (CLADES). In response to these efforts, international donors, such as the InterAmerican Foundation (USA) and the International Development Research Center (Canada), have reoriented their funding priorities to agroecology. Agroecology has also reached the curricula of Latin American universities and the research agenda of international research centers (Bebbington and Thiele 1993).
**Agroecology in Coevolutionary Development**

The heterogeneity and marginalization of peasant livelihood strategies challenge any approach to rural development in Latin America. NGOs applying agroecological methods have responded to this challenge with a technological approach that is radically different from conventional agricultural development. Agroecological technologies strengthen original ecological processes instead of overriding them. The institutional structures supporting research and development relink the social system to the ecological system to allow for local coevolution. Agroecology initiates coevolutionary agroecological development through the following processes:

1. Conceptualizing agriculture as a process following ecological principles gives new knowledge about the behavior and management of diverse agroecosystems.
2. Power is redistributed in the social system through decentralized institutions and popular participation.

Agroecological technology is responsive to the heterogeneity of local conditions for agriculture in Latin America. Agroecologists seek to conduct research on the ecological principles that govern the agricultural field. They expect research results to provide general guidelines, but not detailed recommendations for the design and management of agroecosystem. For example, on the basis of case studies on weed management, agroecologists attempt to determine general ecological principles regulating weed dynamics and interactions in agroecosystems. The findings help establish approaches to analyzing specific crop/weed assemblages in specific local agroecosystems and developing flexible guidelines for the design of farming systems. For each application, agroecologists can then translate the general principles regulating weed dynamics into appropriate recommendations for specific local conditions. In this way, agroecological research is able to develop and adapt technologies to marginal ecological conditions with major limitations for conventional agriculture.

Agroecologists replace the dominance of foreign technology with technologies that address specific local ecological conditions as well as variations in the social system. Peasant agriculture is not transformed but its viability in the given political and socioeconomic circumstances is improved. Agroecology thus recognizes the dependence of production goals from the specific socioeconomic and cultural context. In the context of resource-poor peasants, this often implies emphasizing the stability and sustainability of agricultural production and year-round food security in the same way as productivity. Agroecologists have demonstrated the integrality of peasant livelihood systems and recognize its interdependent subsystems (crop field,
garden, food preparation, off-farm employment, etc.). Projects often integrate the different stages of agricultural production, for example by supporting farmers in the purchase of inputs.

Agroecologists often attempt to diminish peasants' dependency on external forces and strengthen the weak buffers that protect the rural poor from detrimental changes in their social environment. An agroecological emphasis on the use of locally available resources helps reduce the need for external inputs controlled by outside forces. Since peasants lack the risk-sharing or minimizing institutional safety net that protects commercial agriculture, risk minimization becomes a central objective of the ecological design of the production system. For example, the practice of replacing chemical fertilizers with organic fertilizers is a reaction to the high cost of agrochemicals by resource-poor farmers. The use of locally available organic fertilizer increases the stability of peasant livelihood and enhances the often poor productivity of peasants' land in the long term.

Agroecological institutions strengthen local processes against distant forces to allow for local coevolution of the ecological and social systems. Peasants are linked into the process of generating and disseminating technology. The NGOs are generally small and give considerable autonomy to decisions at the local level. Though agroecologists have formed organizations at national and international levels, the need to safeguard responsiveness to local circumstances has been explicitly recognized. Closeness to beneficiaries and personal attitudes and qualifications ensure agroecologists' responsiveness to local needs through two-way information flows and internal learning processes.

Agroecological institution-building brings the various actors in knowledge and technology generation closer together. Integration of the processes of applied research, adaptive trials, technology dissemination, and technology use facilitates close feedback processes between the different phases of technology development and transfer. New knowledge about agricultural systems and information about specific local conditions are generated through increased interactions between farmers, researchers, and extensionists. The rural poor are recognized as rational actors who have formulated livelihood strategies in response to the ecological and social conditions around them. They are understood as key actors in adapting technology to their specific circumstances, and NGOs have developed methodologies that facilitate their participation in research and development.

Farmer participation has become an essential part of agroecological research and development projects. Farmer empowerment is an explicit goal stated in most projects. Generally, agroecological technology empowers peasants by building upon farmers' knowledge, improving their technical skills, and strengthening their capacity to adapt new technologies. In addition, many NGOs emphasize technologies that strengthen group
capacity-building and train farmers as paratechnicians. For example, the dissemination of technological innovations is often based on farmer-to-farmer extension models and small groups of farmers.

Agroecologists, however, have followed two different approaches to farmer participation in their projects (Sikor 1994). Some seek the active involvement of farmers because agroecological technology is information intensive. Farmers participate in on-farm trials, and researchers have direct contact with participating farmers. Others understand the development of peasants' capacity to adapt technological innovations as equally important for the transfer of new technology. They mainly work via local organizations, giving them the possibility to influence the allocation of project resources. In both cases, agroecological NGOs have successfully linked the social and ecological system to allow for local coevolution. Power is redistributed in the social system toward the local level. In the first case, however, agroecological NGOs will be indispensable for the functioning of the system in the long term, requiring very complex and costly institutional arrangements supporting peasant agriculture. In the second case, the NGOs are crucial for creating a positive, reinforcing environment that allows empowerment to take place. In the long term, however, power gets redistributed to peasants, strengthening their capacity to direct the local coevolution between local ecological and social systems in a way that maintains net positive feedback between both systems over time.

Conclusions

To presume that an agricultural failure can be corrected by following the present course a little faster, more intensely pursuing the conventional agricultural development paradigm, appears naïve. Nor can adapting the existing conventional methods to new problems necessarily solve them. Agroecology really is a different approach to agricultural development because it is based on broader philosophical premises than conventional agriculture. It does not reject the currently dominant premises, but it does temper them with additional ways of understanding farming and implementing rural change. Further, by being methodologically pluralistic, it addresses the fact that multiple logics give multiple answers and that experiential judgment and community decision processes are necessary to determine what changes should be implemented.

It has been argued here that a coevolutionary paradigm of development may be complementary with an agroecological approach. Other paradigms, of course, will also give helpful insights. The strengths of the coevolutionary paradigm, however, appear to identify some of the key differences between agroecology and conventional agriculture. The paradigm very readily illustrates how social and environmental systems are intertwined, each
reflecting the other, yet each changing in response to the other. This helps us understand why social and environmental change must occur together. It easily shows why agroecologists prefer to experiment within farms, adapting existing systems of farming rather than radically redesigning agriculture. The coevolutionary perspective, furthermore, gives legitimacy to farmers' knowledge and helps explain why change must include them in the experimental process.

Technologies and institutions using an agroecological approach have a significant potential for resolving the problems of rural poverty, food insecurity, and environmental degradation. While much of the success of agroecology has been in developing countries, many of the same problems occur in the developed countries where an agroecological approach might also sustain rural communities. Latin American NGOs applying agroecological methods have developed a new approach to technology generation and rural development that facilitates coevolutionary development. The NGOs have acted within the given political and socioeconomic framework, characterized by the political primacy of urban social groups, the region's heavy dependence on industrial production, the absence of effective land distribution, subsidies for fossil-fuel based agricultural inputs, and the limited access of peasants to political and economic resources. Under these conditions, low-external input practices have in many circumstances proven to be economically, socially, culturally, and ecologically most appropriate for those farmers who have not benefitted from conventional agriculture.
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.
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, predation, competition, low reproduction, and so on.

9. Changes and fluctuations in the environment (exploitation, disturbance, 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.

<table>
<thead>
<tr>
<th>Type of Determinants</th>
<th>Factors</th>
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<tbody>
<tr>
<td>Physical</td>
<td>Radiation</td>
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<td></td>
<td>Temperature</td>
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<td></td>
<td>Rainfall, water supply (moisture stress)</td>
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<td></td>
<td>Soil conditions</td>
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<td></td>
<td>Slope</td>
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<td></td>
<td>Land availability</td>
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<tr>
<td>Biological</td>
<td>Insect pests and natural enemies</td>
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<td></td>
<td>Weed communities</td>
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<td></td>
<td>Plant and animal diseases</td>
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<td>Soil biota</td>
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<td>Background natural vegetation</td>
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<td></td>
<td>Photosynthetic efficiency</td>
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<td></td>
<td>Cropping patterns</td>
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<td></td>
<td>Crop rotation</td>
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<td>Socioeconomic</td>
<td>Population density</td>
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<td></td>
<td>Social organization</td>
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<td></td>
<td>Economic (prices, markets, capital, and credit availability)</td>
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<td></td>
<td>Technical assistance</td>
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<td></td>
<td>Cultivation implements</td>
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<td></td>
<td>Degree of commercialization</td>
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<td></td>
<td>Labor availability</td>
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<tr>
<td>Cultural</td>
<td>Traditional knowledge</td>
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<td>Beliefs</td>
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<td>Ideology</td>
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<td>Gender issues</td>
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<td></td>
<td>Historical events</td>
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TABLE 3.2 Factors influencing agricultural intensification in African regions where shifting cultivation is practiced (Protheroe 1972).

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<thead>
<tr>
<th>FACTOR</th>
<th>PROCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>POPULATION</td>
<td>Low density → Increasing numbers → High density</td>
</tr>
<tr>
<td>SYSTEM</td>
<td>Shifting cultivation → Rotational cultivation/fallow → Semi-permanent/permanent cultivation → Increasing length of cultivation period → Decreasing length of fallow period → Manuring and fertilizing</td>
</tr>
<tr>
<td>CROPS</td>
<td>Subsistence food crops → Decreasing importance → Cash (food and export) crops → Increasing importance</td>
</tr>
<tr>
<td>TENURE</td>
<td>Communal right to land → Communal rights decreasing → Individual rights to land → Individual rights increasing</td>
</tr>
<tr>
<td>Land allocation by need → Land transfer by pledge, rent, lease, and sale</td>
<td></td>
</tr>
<tr>
<td>Fragmented/dispersed holdings → Consolidated holdings</td>
<td></td>
</tr>
<tr>
<td>No permanent demarcation of holdings → Permanent demarcation of holdings</td>
<td></td>
</tr>
<tr>
<td>SETTLEMENT</td>
<td>Impermanent/migratory → Increasing permanence and nucleation → Permanent/fixed nucleated and dispersed</td>
</tr>
<tr>
<td>SMALL VILLAGES/DISPERSED</td>
<td></td>
</tr>
<tr>
<td>EXCHANGE</td>
<td>Nonexistent/local → Increasing involvement at local, regional, national, and international levels MARKETS</td>
</tr>
</tbody>
</table>
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., the 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 output 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, nonsymbiotic 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).

<table>
<thead>
<tr>
<th>System</th>
<th>Output/Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-industrial stage (labor intensives, Mexico)</td>
<td>30.6</td>
</tr>
<tr>
<td>Pre-industrial stage (labor intensives, Guatemala)</td>
<td>13.6</td>
</tr>
<tr>
<td>Semi-industrial stage (animal fraction, Mexico)</td>
<td>4.87</td>
</tr>
<tr>
<td>Full-industrial stage (mechanized, USA)</td>
<td>2.58</td>
</tr>
</tbody>
</table>

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 evapotranspiration 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.
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 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>
<thead>
<tr>
<th>Characteristics</th>
<th>Agroecosystem</th>
<th>Natural Ecosystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net productivity</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Trophic chains</td>
<td>Simple, linear</td>
<td>Complex</td>
</tr>
<tr>
<td>Species diversity</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Genetic diversity</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Mineral cycles</td>
<td>Open</td>
<td>Closed</td>
</tr>
<tr>
<td>Stability (resilience)</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Entropy</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Human Control</td>
<td>Definite</td>
<td>Not needed</td>
</tr>
<tr>
<td>Temporal permanence</td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td>Habitat heterogeneity</td>
<td>Simple</td>
<td>Complex</td>
</tr>
<tr>
<td>Phenology</td>
<td>Synchronized</td>
<td>Seasonal</td>
</tr>
<tr>
<td>Maturity</td>
<td>Immature, early</td>
<td>Mature, climax</td>
</tr>
<tr>
<td></td>
<td>successional</td>
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</tr>
</tbody>
</table>
prevent destructive oscillations in 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 populations. 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 producing communities improves (Douglass 1984).
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.
For this reason, the concept of stability must be expanded to embrace socio-economic 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).

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

*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 tropics (NRC 1993).

<table>
<thead>
<tr>
<th>Land Use Systems</th>
<th>Nutrient Cycling Capacity b</th>
<th>Soil and Water Conservation Capacity</th>
<th>Stability Towards Pests and Diseases g</th>
<th>Biodiversity Level h</th>
<th>Carbon Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensive cropping</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>L M H</td>
<td>L M H</td>
</tr>
<tr>
<td>High-resource areas</td>
<td>X f</td>
<td>X</td>
<td>X O</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Low-resource areas</td>
<td>X O</td>
<td>X O</td>
<td>X O</td>
<td>X O</td>
<td>X</td>
</tr>
<tr>
<td>Low-intensity shifting</td>
<td>X</td>
<td>X O</td>
<td>X</td>
<td>X</td>
<td>X O</td>
</tr>
<tr>
<td>cultivation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agropastoral systems</td>
<td>X</td>
<td>X O</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cattle ranching</td>
<td>X</td>
<td>X O</td>
<td>X</td>
<td>X O</td>
<td>X</td>
</tr>
<tr>
<td>Agroforestry</td>
<td>X</td>
<td>X O</td>
<td>X O</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mixed tree systems</td>
<td>X</td>
<td>X O</td>
<td>X</td>
<td>X</td>
<td>X O</td>
</tr>
<tr>
<td>Perennial tree crop</td>
<td>X</td>
<td>X O</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>plantations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regenerating and</td>
<td>X</td>
<td>X O</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>secondary forests</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural forest management</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X O</td>
</tr>
<tr>
<td>Modified forests</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Forest reserves</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

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

a In this assessment, "X" denotes results using the best widely available technologies for each land use system. 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) research 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 recycling and of nutrient containment.
<table>
<thead>
<tr>
<th>Social Attributes</th>
<th>Economic Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health and Nutritional Benefits</td>
<td>Cultural and Communal Viability</td>
</tr>
<tr>
<td></td>
<td>Political Acceptability</td>
</tr>
<tr>
<td>Required External Inputs</td>
<td>Employment Per Land</td>
</tr>
<tr>
<td><strong>L M H</strong></td>
<td><strong>L M H</strong></td>
</tr>
<tr>
<td>X O</td>
<td>X</td>
</tr>
<tr>
<td>X O</td>
<td>X O</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>X O</td>
<td>X O</td>
</tr>
<tr>
<td>X O</td>
<td>O</td>
</tr>
<tr>
<td>X</td>
<td>X O</td>
</tr>
<tr>
<td>X</td>
<td>X X O</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>X O</td>
<td>X O</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

---

- **a** Indicates the natural ability to maintain pests and diseases below economic threshold levels in tropical ecosystems.
- **b** Refers to the diversity of plant and crop species which, in turn, fosters diversity of flora and fauna both above and below the ground.
- **c** Assumes diversity of plant species under well-managed grazing systems, which may include tree species in silvipastoral systems.
- **d** To farms and their local communities.
- **e** The ability to survive as a land use system, to provide income, employment, and the needed 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.
- **f** 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.
- **g** 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.
- **h** 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 net economic 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 $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.**

<table>
<thead>
<tr>
<th>NET FARM INCOME ($/acre/year)</th>
<th>w/o Natural Resource Accounting</th>
<th>w/ Natural Resource Accounting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Operating Margin</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>- Soil Depreciation</td>
<td>–</td>
<td>25</td>
</tr>
<tr>
<td>Net Farm Operating Income</td>
<td>45</td>
<td>20</td>
</tr>
<tr>
<td>+ Government Commodity Subsidy</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Net Farm Income</td>
<td>80</td>
<td>55</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>NET FARM INCOME ($/acre/year)</th>
<th>w/o Natural Resource Accounting</th>
<th>w/ Natural Resource Accounting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Operating Margin</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>- Soil Depreciation</td>
<td>–</td>
<td>25</td>
</tr>
<tr>
<td>Net Farm Operating Income</td>
<td>45</td>
<td>20</td>
</tr>
<tr>
<td>- Off-site Costs</td>
<td>–</td>
<td>47</td>
</tr>
<tr>
<td>Net Economic Value</td>
<td>80</td>
<td>-27</td>
</tr>
</tbody>
</table>
PART TWO

The Design of Alternative Agricultural Systems and Technologies
Over the past century, abundant resources, cheap energy, technological innovation, and cultural factors have fueled agricultural growth in industrialized countries. Most agricultural development projects have aimed at increasing production of agricultural commodities and linkages to markets (Perelman 1977, Conway 1985). This emphasis on increasing agricultural output was transferred to developing countries, without considering ecological and socioeconomic conditions, and it was justified by viewing the problems of rural poverty and hunger largely as problems of production. Consequently, the techniques of agricultural development have not accounted for the needs and potentials of local farmers.

Consequences of Inappropriate Technology

Examples of the environmental consequences of dramatic technological changes abound in less-developed countries. One example is the substitution of tractor for buffalo power in Sri Lanka (Senanayake 1984). At first sight, this substitution seemed to involve a simple trade-off between more timely planting and labor saving on one hand, and the provision of milk and manure on the other. However, buffaloes create buffalo wallows, and these, in turn, provide a surprising number of benefits. In the dry season, they are a refuge for fish, which then move back to the ricefields in the rainy season. Some fish are caught and eaten by the farmers and by the landless, providing valuable protein; other fish eat the larvae of mosquitoes that carry malaria. The thickets surrounding the wallows harbor snakes that eat rats (that eat...
rice) and lizards that eat the crabs that make destructive holes in the ricebuds. The wallows are also used by the villagers to prepare coconut fronds for thatching. If the wallows go, so do these benefits. The adverse consequences may not stop there. If pesticides are used to kill the rats, crabs, or mosquito larvae, pollution or pesticide resistance becomes a problem. Similarly, if tiles are substituted for thatch, forest destruction is hastened since firewood is required to fire the tiles (Conway 1986).

Another clear example of inappropriate technology is the Green Revolution, which attempted to solve crop production problems in the Third World through the development of high-yielding cereal varieties requiring massive inputs of pesticides, fertilizers, irrigation, and machinery (Perelman 1977). Contrary to expectations, no significantly new technological packages capable of increasing yields could be offered to the majority of small farmers (de Janvry 1981). The new packages failed to take into account the features of subsistence agriculture, ability to bear risk, labor constraints, symbiotic crop mixtures, and diet requirements, factors that determine the management criteria and levels of resource use by local farmers. In the majority of cases, new varieties could not surpass local varieties when managed with traditional practices (Perelman 1977). The areas where the new "miracle cereals" were widely adopted were haunted by disease epidemics. Plant breeders soon learned that planting an entire region with genetically similar varieties could lead to disastrous attacks by either insect pests or diseases (Adams et al. 1971). Farmers soon abandoned the new varieties because of their high production costs (de Janvry 1981). For example, most small farmers could not afford the tubewell needed for irrigation, an essential component of the new technology (Perelman 1977). Thus, it seems that only a small proportion of farmers benefitted from the Green Revolution.

Farming Systems Research

One of the key factors in modern agricultural development is the availability of an organized research, educational, and extension infrastructure. Although in most countries there is such a network, with few exceptions, it is specifically directed to the needs and problems of small farmers. However, most agricultural research has benefitted those individuals with ready access to capital: large farmers and agribusinesses (Busch and Lacy 1983). In pest control, for example, an estimated 92 percent of the research effort is focused on the use of herbicides, and 55 percent and 89 percent, respectively, of the research is focused on applied pesticide tactics in insect and pathogen control (Pimentel 1973). Also, virtually no researchers are examining alternative approaches to agricultural production, and therefore the wealth of information that can be extended to these farmers, even if a network existed, is very limited.
Clearly, the generation of technologies adapted to small farmers' needs must emerge from integrated studies of the natural and socioeconomic circumstances that influence their farming systems and dominate their responses to alternative technologies. Many circumstances influence the type of cropping system or management practice a farmer chooses. Natural circumstances (climate, soil, pests, diseases) impose biological constraints on the crop system. On the other hand, many socioeconomic circumstances (transportation, capital, markets, labor, farm inputs, credit, technical assistance) affect the external environment that condition farmers' decisionmaking. By conducting multidisciplinary research in selected farmers' fields, and by analyzing the socioeconomic, technical, and ecological constraints facing crop production on these farms, important feedback is obtained about farm conditions, management practices, and farmers' needs. This information can then be incorporated into research decisions conducive to the development of technologies adapted to farmers' needs and resources.

Detailed descriptions of research methodologies attuned to actual conditions of traditional farmers of the developing world available (Harwood 1979; Hildebrand 1979; Byerlee et al. 1980; Zandstra et al. 1981; and Shaner et al. 1982). These methodologies emerged in response to the critics of internationally funded rural development, who charge that in the past, programs lacked an understanding of the ecological and socioeconomic milieu in which they operated, excluded the small farmers as both collaborators and beneficiaries, and ineptly promoted inappropriate technology.

The most common methodology, termed farming systems research (FSR), has many variants, but in general, entails an understanding of farming systems. A multidisciplinary team gathers relevant information on the selected zone by analyzing background data from published or unpublished materials, conducting field surveys that include interviews with farmers and others knowledgeable about farm circumstances, and by field observations. From the survey, researchers can formulate hypotheses about why farmers use these particular practices (Figure 4.1)

FSR is considered a problem-oriented approach to agricultural research that begins by diagnosing the conditions, practices, and problems of particular groups of farmers. Once the problems are identified, a research program is designed to address them. A key part of any such program is conducting experiments on farmers' fields under farmers' conditions and management. Those experiments are then evaluated using criteria that are important to farmers, and the results are used to make recommendations.

**FSR Variants and Prototypes**

**Sondeo's Approach.** In the early seventies, in Guatemala, Hildebrand (1981) developed the Sondeo approach, which entails a creative combination of
disciplines (agronomy, animal science, and socioeconomics) to conduct rapid appraisals for generating new technology. A team visits a region of homogeneous farming systems and practices, attempting to understand the agroecosystems and to identify appropriate technological improvements. Ideas about improved farm practices emerge from discussions between scientists and farmers and are tried through on-farm trials by a technology testing team.
**IRRI’s and CIMMYT’s Approach.** In the late 1970s and early 1980s, CGIAR (Consultative Group on International Agricultural Research) scientists, mainly from CIMMYT (Centro Internacional de Mejoramiento de Maíz y Trigo) and IRRI (International Rice Research Institute), developed farming systems research to be applied in Latin America and southeast Asia, which followed a logical sequence of steps (Harwood 1979a; Byerlee et al. 1980):

1. **Selection of the target area.** Within regions, cropping systems and farmers’ practices vary considerably. Sites with similar relative cropping patterns, agroclimatic characteristics, and economic circumstances are selected by multidisciplinary teams, usually a group of economists, sociologists, agronomists, and plant protectionists.

2. **Description of the environment.** Data are collected on climate, soil, topography, rainfall, drought, hydrology, temperature, day length, soil fertility, slope, insect pests, diseases, and weeds.

3. **Field surveys.** The field survey includes a biophysical description and a socioeconomic evaluation. The biophysical component entails (a) identifying land types at the site, (b) identifying existing crops, cropping patterns, and systems (like rotations, polycultures), (c) describing cropping systems determinants, (d) describing farm types and the resource base at the site, and (e) identifying farming system interactions, including those between crops and livestock, like complementarities such as crop residues used for cattle feed and manure used as fertilizer. Researchers also describe the management practices by following the checklist described in Table 4.1. The socioeconomic component of the survey analyzes the resources that go into cropping systems. Farm resources are listed in Table 4.2. Cash from sale of crops, animal products, handicrafts, and from other sources is also recorded. Cost and return analysis is used to measure the economic benefits of a new technology at the field level. A whole-farm analysis measures the economic benefits of both new and historical agricultural techniques in the context of all the economic activities, including other agricultural enterprises and household and off-farm operations. The major resources of land, labor, and capital are all valued with due regard to their actual availability and to the demand that exists for them at a particular time. Recommendations derived from cost/benefit data should be consistent with the farmers' desire to increase income and avoid risk and with the scarcity of investment capital (Perrin et al. 1979).

This FSR methodology suffered continual evolution and the latest version developed by CIMMYT and CIAT (Centro Nacional de Agricultura Tropical) scientists (Tripp and Woolley 1989) entails a six-step planning process (Figure 4.2):

**Step 1:** List problems that limit the productivity of the farming system.
TABLE 4.1 A checklist of information on crop management practices to be recorded in each farm throughout the year (Byerlee et al. 1980).

<table>
<thead>
<tr>
<th>Land Preparation</th>
<th>Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence of operations.</td>
<td>Timing of harvest in relation to maturity.</td>
</tr>
<tr>
<td>Timing of each operation in relation to rains.</td>
<td>Methods of harvesting.</td>
</tr>
<tr>
<td>Equipment used in each operation.</td>
<td>Use of leaves and tops for animals.</td>
</tr>
<tr>
<td>Variation in method with seasonal conditions.</td>
<td>Timing and method of picking leaves and tops.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Planting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety(ies) used.</td>
</tr>
<tr>
<td>Density and spacing.</td>
</tr>
<tr>
<td>Time of planting in relation to rains, frosts, etc.</td>
</tr>
<tr>
<td>Spread of planting dates.</td>
</tr>
<tr>
<td>Sequence of interplanting crops.</td>
</tr>
<tr>
<td>Method of planting (hills, broadcast, etc.).</td>
</tr>
<tr>
<td>Method of covering seed.</td>
</tr>
<tr>
<td>Practices of replanting sections of whole fields.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thinning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method and timing.</td>
</tr>
<tr>
<td>Target density.</td>
</tr>
<tr>
<td>Use of thinnings.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of weedings.</td>
</tr>
<tr>
<td>Timing each in relation to planting.</td>
</tr>
<tr>
<td>Equipment used in weeding.</td>
</tr>
<tr>
<td>Use of herbicides (type, rate, timing and method of application).</td>
</tr>
<tr>
<td>Use of weeds.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fertilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of fertilizer(s), including organic.</td>
</tr>
<tr>
<td>Rate(s) of application.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Timing of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment used for application.</td>
</tr>
<tr>
<td>Method of application (e.g., broadcast, furrows, etc.).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pest Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of control (type, rate, equipment).</td>
</tr>
<tr>
<td>Timing of control.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of irrigation.</td>
</tr>
<tr>
<td>Frequency and timing of irrigation.</td>
</tr>
</tbody>
</table>
TABLE 4.2 Main resources of farming systems to be evaluated (Shaner et al. 1982).

LAND
- Size of farm
- Ownership
- Permanency of use
- Landlord/tenant relationships
- Land quality (soil depth, texture, and presence of toxic substances)
- Terrain (slope, whether or not terraced)
- Water availability (nearness of ponds or streams for livestock, irrigated or rainfed farming, dependability of supply)
- Location (access to markets and other services)

LABOR
- Members of the household or hired workers. Some relevant characteristics are:
  - Number, age, and sex of family members and workers
  - Level of productivity and health
  - Division of time between on-farm and off-farm activities
  - Extent and nature of cooperative efforts
  - Other responsibilities that influence allocation of time and effort

CAPITAL
- Physical and financial assets that include:
  - Tools and equipment
  - Building and improvements to the land
  - Livestock and other assets capable of being sold to meet the farmer's needs

These problems could be biological limiting factors or inefficiencies in resource use.

Step 2: Rank in order of importance, identified problems, including the scope of the problem and the yield loss attributable to the problem.

Step 3: Analyze the cause of problems for which there is enough evidence. Causes may be natural, socioeconomic or cultural practices.

Step 4: Analyze interrelations among problems and causes.

Step 5: List solutions to those problems for which researchers have sufficient evidence and whose cases are understood well enough to suggest possible solutions.

Step 6: Identify factors for experimentation in order to evaluate proposed solutions.

D and D Methodology of ICRAF
(International Centre for Research in Agroforestry)

ICRAF’s diagnosis and design (D and D) methodology identifies promising candidate agroforestry technologies (Raintree and Young 1983). Major emphasis
Further evidence required to determine causes of problems.

Evaluate solutions.

Analyze interrelations among problems and causes.

Identify causes.

Rank problems.

Identify problems.
is placed on the farm household management unit and the satisfaction of its needs. The methodology also seeks to address a broader range of production and conservation objectives than most farming systems research methods, emphasizing productivity, sustainability, and adaptability. A minimal team includes one or more representatives of agricultural science (general agronomy, horticulture, and livestock sciences), forestry (in the broadest sense), social science (sociology/anthropology, human geography, and economics), and natural sciences concerned with land resource survey (ecology, soils science, climatology). The application of D and D procedures by a multidisciplinary team usually entails about two weeks to carry out the diagnostic survey, analyze the results, and develop appropriate design concepts for agroforestry interventions to improve the existing land use system. It is a four-stage procedure: prediagnostic, diagnostic, design and follow-up planning. The D and D procedure is seen as part of a continuing learning process and may be repeated.

**CIP's (Centro Internacional de la Papa) Farmer-Back-to-Farmer**

The original farmer-back-to-farmer research was conducted on potato storage in Peru by biological scientists and an anthropologist following 25 years of failure in potato storage work (Rhoades and Booth 1982). The anthropologist learned about farm families' objectives and their knowledge of, and problems with, potato storage and acted as a link between them and the biological scientists, bringing the latter into direct learning contact with the farmers. There were four stages: establishing a common definition of the problem; interdisciplinary team research seeking a solution; testing and adaptation of the proposed technology on-farm, with farmers contributing ideas, and farmer evaluation. The result was an improved and adoptable technology which met farmers' objectives, used materials to which they had access, fit in with their traditional house design, and, above all, was adopted by them. A key element was change of perception and priority on the part of the scientists. For example, what appeared to be losses to scientists were not necessarily losses to farmers, who had uses for shrivelled or spoiled potatoes.

**Technology Research and Evaluation**

In most methodologies, interpretation of the survey data allows researchers to plan experiments in farmers' fields. A group of farmers is selected to help design, test, and evaluate experiments. A broad cross section of farmers must be included to avoid biasing the recommendations toward farmers of
recognized ability. Experiments are designed to test particular component technologies (varietal selection, tillage and crop establishment methods, fertilization, and pest management strategies) against farmers' current practices. A guiding principle is that the component technology should fit the resource limits of most farmers in the region, and should therefore be environmentally sound, socially acceptable, and economically viable. However, the farmer should be able to decide freely which innovations are to be made on his or her land. A crop innovation may disturb the farmer's economic equilibrium and therefore requires a period of adjustment (Zandstra et al. 1981).

The productivity of the system should not be evaluated solely on the basis of crop yield per unit of land, but should incorporate the farmers' perspectives on productivity, emphasizing maximization of returns for the most limiting factor (such as labor, money, input). When the short-term economic performance of the cropping pattern is emphasized, the recommended technologies almost invariably further the use of chemical and mechanized technologies, typical of capital-intensive agriculture (Perelman 1977).

Field trials usually include treatments that simulate and test the farmers' management level (which may not include any purchased material inputs), incorporate the technology thought to be optimal for the cropping pattern and evaluate a third level of inputs that are expected to produce still higher yields (Zandstra et al. 1981). Experiments must be repeated for two to five years to demonstrate the adaptation of new technologies to local conditions.

This methodology (Figure 4.3) could operate in the following way (Hart 1978). Suppose maize and cassava are commonly intercropped in a humid tropical environment on farms of five hectares or less, with gross annual incomes between $500 and $1,000. A research team would analyze the agroecosystem in which the maize and cassava crop system is a subsystem, and the farm system in which the farmer's agroecosystem management plan operates. The team would then recommend modifications of the farmer's practices to improve annual income through increased crop yield. For example,

![FIGURE 4.3 Methodological sequence in the modification of farmer's agroecosystem management plan (Hart 1978).](image-url)
the team might recommend a different maize variety, a change in the planting distance between the maize and cassava, more fertilizer or manure, or all three modifications. This methodology increasingly emphasizes farmers' participation, as working with farmers throughout the research process and modifying experiments as indicated by observations and responses of farmers ensures easier acceptance and adoption of technologies. Farmers often experiment and their innovations provide useful foundations for further scientific exploration. Regular interaction with farmers alerts scientists to the multiple problems farmers face.

Rapid Rural Appraisal (RRA) and Agroecosystem Analysis (AEA)

Due to the need for more rapid multidisciplinary diagnosis, a new method of Rapid Rural Appraisal (RRA), entitled Agroecosystem Analysis (AEA), was developed by Conway and Barbier (1990). Although similar to FSR methods described earlier, AEA differs in various respects:

1. An emphasis on the use of multidisciplinary workshops and rapid appraisal techniques
2. A foundation on ecological as well as socioeconomic concepts
3. A recognition of the importance of the trade-offs in agricultural development between productivity, stability, sustainability, and equitability
4. Its applicability not only to farming systems but to the analysis and development of larger systems at the village, watershed, regional, and even national level

By absorbing relevant ideas from anthropology and numerous other sources including agroecology, RRA has acquired a distinct tool kit of techniques and a clear philosophy characterized by being:

1. Iterative: goals and processes modified through learning by doing
2. Innovative: techniques adapted to each new problem, rather than applied according to a fixed procedure
3. Interactive: interdisciplinary
4. Informal: avoid use of predetermined questionnaires
5. In the community: learning takes place through exchange of ideas with rural people in the field

The aim of the multidisciplinary team is to arrive at a sufficiency of knowledge of the key agroecosystems processes and properties, concentrating only on relevant aspects and details. AEA uses a diversity of analyses from several sources and means of obtaining information, such as secondary
data, direct field observations, semi-structured interviews, and the preparation of diagrams. Local inhabitants are constantly consulted and participate actively in the elaboration of diagrams, analytical games, dialogues and workshops. Depending on the objectives and types of information needed, there are different classes of RRA:

**Exploratory RRA.** Used to obtain information about a new topic or agro-ecosystem. The output is usually a set of preliminary key questions and hypotheses.

**Topical RRA.** Used to investigate a specific topic, often in the form of a key question and hypothesis generated by the exploratory RRA. The output is usually a detailed and extended hypothesis that can be used as a strong basis for research or development.

**Participatory RRA.** Used to involve villagers and local officials in decisions about further action based on the hypotheses produced by the exploratory or topical RRAs. The output is a set of farmer-managed trials or a development activity in which the villagers are closely involved.

**Monitoring RRA.** Used to monitor progress in the trials and experiments and in the implementation of development activity. The output is usually a revised hypothesis together with consequent changes in the trials or development intervention which will hopefully bring about improved benefits.

The advent of RRA has thus greatly enriched the availability of methods of analysis for rural development. Techniques can be chosen on the basis of the nature of the problem, the local situation, and the resources at hand. In particular, different techniques, both formal and informal, can be blended to produce a project cycle along the lines of Figure 4.4, which can be applied to a wide range of projects, both large and small. In such a scheme, the primary role of the RRA is to define and refine hypotheses, which are then tested, either formally or informally, as part of the project cycle, assuming the cycle is iterative, flexible, and open. RRA advocates believe that it should be possible to combine speed with both rigor and sensitivity resulting in development that is not only productive but durable and equitable in its benefits.

**Steps in RRA**

**Site Selection.** Sites for RRA analysis are picked either through requests from the community or upon the recommendation of an extension officer or government official. Locations tend to be places where there have been prolonged ecological difficulties or downturns in productivity.

**Preliminary Visits.** A team generally consists of four to six specialists in water, soil, forestry, livestock, community development, and other skills related to natural resources management, which meets with village leaders before starting an RRA to clarify what RRA will do as well as what it will not do.
FIGURE 4.4 A model for project design and implementation which combines the use of Rapid Rural Appraisal and formal analysis and survey (after Conway and Barbier 1990).
Data Collection. There are four basic data sets to be gathered:

1. **Spatial Data.** Includes a village sketch map compiled in cooperation with village leaders to identify physical and economic details and to locate the community’s infrastructure.

   A village transect, with cooperation from residents, to identify types of land use, problems, and opportunities to solve problems. The transect also helps the team to determine whether there are sub-zones within the community that require special consideration (Figure 4.5).

   Farm sketches representative of households in the community. Six to eight farms are identified, representing examples of the ecological, income, land use, and ethnic variation present in the community.

2. **Time-related Data.** The team meets with residents (including young and old, men and women) to discuss what they consider to be the most important events in the community’s past and prepare a time line.

   Trend lines are developed, based on village perspectives, of a thirty- or forty-year pattern of changes in resource issues, such as rainfall, crop production, soil loss, deforestation, health, population, and other topics of concern to the community.

   The team organizes a seasonal calendar, using data on topics such as land use, hunger, disease, food surplus, and cash availability, which are organized and entered into a time scale of 12 to 18 months.

3. **Institutional Data.** The RA team also gathers data about village institutions. Groups of residents are asked to rank community institutions in order of importance and to construct diagrams that indicate the relationships between and among village units.

4. **Technical Data.** In addition to the temporal, spatial, and social data, the team assembles information on economic and technical feasibility, that is, water or soils needed to help villagers rank project activity.

Data Synthesis and Analysis. The team, sometimes with one or two village leaders, organizes the collected data and compiles a list of problems and opportunities for possible action.

**Ranking of Problems.** Villagers come together to rank the listed problems. In some cases, the team members lead the discussion. The outcome is a set of problems that village groups agree are ranked from most to least severe.

**Ranking of Opportunities.** Village groups then rank opportunities and solutions that address the highest priority problems. Different strategies are possible to achieve consensus about the most feasible opportunities. Criteria for ranking include stability, equity, productivity, sustainability, and feasibility. Technical officers play an important role in this discussion so that solutions will be feasible in technical, economic, ecological, and social terms.

**Adoption of a Village Resource Management Plan (VRMP).** The highest priority solutions are organized into a VRMP, which takes the form of a contract between village groups, technical officers, NGOs (if any are involved), and
external groups (such as a donor or international agency).

**Implementation.** Once the VRMP is completed, it is time to do the work. Follow-up reveals that the best results have been achieved when a village leader has taken the lead, and when the actual work has been performed primarily by the community's self help groups.

Perhaps the most important aspect of RRA is the possibility of developing a truly participatory technology development (PTD) approach. Viability of PTD requires the building of a set of relationships between development workers and local people. The six basic types of activities in the PTD process and examples of methods related to them are outlined in Table 4.3.
<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Examples of operational</th>
<th>Examples of output indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Getting Started</td>
<td>Building relationships for cooperation. Preliminary situation analysis.</td>
<td>Organizational resources inventory.</td>
<td>Inventories.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Community walk.</td>
<td>Protocols for community participation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Screening secondary data.</td>
<td>Core PTD network.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Problem census.</td>
<td>Enhanced agroecological awareness.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Community survey.</td>
<td></td>
</tr>
<tr>
<td>try</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity</td>
<td>Description</td>
<td>Examples of operational</td>
<td>Examples of output indicators</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Sharing the results</td>
<td>Communicating basic ideas and principles, results, and PTD process. Training in skills, proven technologies, and use of experimental methods.</td>
<td>Visits to secondary sites. Farmer-to-farmer training. Farmers' manuals and audiovisuals. Field workshops.</td>
<td>Spontaneous diffusion of ideas and technologies. Enhanced local capacity for farmer-to-farmer training and communication. Increasing number of villages involved in PTD.</td>
</tr>
</tbody>
</table>
Designing Sustainable Agroecosystems

The search for self-sustaining, low-input, diversified, and energy-efficient agricultural systems is now a major concern of some researchers, farmers, and policymakers worldwide. A key strategy in sustainable agriculture is to restore agricultural diversity of the agricultural landscape (Altieri 1987). Diversity can be enhanced in time through crop rotations and sequences in time and space in the form of cover crops, intercropping, agroforestry crop/livestock mixtures, and so forth. Vegetation diversification not only results in pest regulation through restoration of natural control, but also produces optimal nutrient recycling, soil conservation, energy conservation, and less dependence on external inputs.

Sustainable agriculture generally refers to a mode of farming that attempts to provide long-term sustained yields through the use of ecologically sound management technologies. This requires that agriculture be regarded as an ecosystem (hence, the term agroecosystem) and, as such, farming and research are not concerned with high yields of a particular commodity but rather with the optimization of the system as a whole. It also requires looking beyond production economics and considering the vital issue of ecological stability and sustainability.

Choosing an Agricultural System

The first step in designing an agricultural system is to conceptualize it. Any concept of an agricultural system must include at least the following (Spedding 1975):

- **Purpose:** Why the system is being established
- **Boundary:** Where the system begins and ends
When envisioning an agroecosystem, it is important to consider the following key ideas:

1. Agroecosystems are a collection of abiotic and biotic components linked to form an ecological working unit.
2. Agroecosystems can be set up as self-regulating within defined limits.
3. Agroecosystems vary according to the nature of their components, assemblage in time and space, and level of human management.
4. No agroecosystem is a completely independent unit and biologically rarely have well-defined boundaries.
5. Agroecosystems can be of any biogeographical scale.

The next step is to match the needs of the conceptualized system as closely as possible with the local constraints, conditions, and available resources (Spedding 1975). The considerations that determine the feasibility, profitability, practicality, and preferences are summarized in Table 5.1.

Clearly, environments differ both in resources and constraints, and in the extent to which these can be modified. Resource needs can also be modified somewhat but all modifications involve some cost. In general, systems based on annual staple crops require less investment and environmental modification than specialty vegetable or fruit crop systems (Table 5.2).

**TABLE 5.1** Factors affecting the choice of farming systems (after Spedding 1975).

<table>
<thead>
<tr>
<th>Ecological factors</th>
<th>Infra-structural features</th>
<th>External economic constraints</th>
<th>Internal operational factors</th>
<th>Personal acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climatic</td>
<td>Land tenure</td>
<td>Markets</td>
<td>Farm size</td>
<td>Personal preferences</td>
</tr>
<tr>
<td>Soil</td>
<td>Water supply</td>
<td>Communica 4-ions</td>
<td>Labor availability</td>
<td></td>
</tr>
<tr>
<td>Biological</td>
<td>Power supply</td>
<td>Credit availability</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 5.2 Some factors favoring success in modern agroecosystems (after Thorne Thorne 1979).

<table>
<thead>
<tr>
<th>Factors</th>
<th>Field Crop Requirements</th>
<th>Vegetable, fruits or special crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of farm</td>
<td>Variable, small to large if mechanized for harvesting</td>
<td>Variable, small to medium</td>
</tr>
<tr>
<td>Climate</td>
<td>Limits, kinds and varieties of crops</td>
<td>A restriction for many specific crops especially frosts</td>
</tr>
<tr>
<td>Soil</td>
<td>Classes I to III depending on soil conservation practices</td>
<td>Class I, but many crops have special requirements (flat soils, high fertility, etc.)</td>
</tr>
<tr>
<td>Water</td>
<td>Good water supply, can adapt to some arid conditions</td>
<td>Needs good water supply</td>
</tr>
<tr>
<td>Labor requirements</td>
<td>Varied</td>
<td>Generally high</td>
</tr>
<tr>
<td>Specialized labor</td>
<td>Medium</td>
<td>High for some crops</td>
</tr>
<tr>
<td>Capital investment, machinery, buildings</td>
<td>Varied</td>
<td>Generally high</td>
</tr>
<tr>
<td>Fertilizer requirements</td>
<td>High, especially nitrogen</td>
<td>High and varied. Many require micronutrients</td>
</tr>
<tr>
<td>Pest control</td>
<td>Varied depending on plant diversity</td>
<td>High for some crops demanding high cosmetic quality</td>
</tr>
<tr>
<td>Use of crop rotations</td>
<td>Varied</td>
<td>Varied, lacking in fruit crops</td>
</tr>
</tbody>
</table>

Elements of Sustainability

The basic tenets of a sustainable agroecosystem are conservation of renewable resources, adaptation of the crop to the environment, and maintenance of a high but sustainable level of productivity. To emphasize long-term ecological sustainability rather than short-term productivity, the system must:

- Reduce energy and resource use
- Employ production methods that restore homeostatic mechanisms conducive to community stability, optimize the rate of turnover and recycling of matter and nutrients, maximize the multiple-use capacity of the landscape, and ensure an efficient energy flow
• Encourage local production of food items adapted to the natural and socioeconomic setting
• Reduce costs and increase the efficiency and economic viability of small and medium-sized farms, thereby promoting a diverse, potentially resilient agricultural system

Thus a key point to the design of sustainable agroecosystems is to understand that there are two fundamental ecosystem functions that must be enhanced in agricultural fields: biodiversity of microorganisms, plants and animals, and biologically mediated recycling of nutrients from organic matter. As shown in Figure 5.1, from a management viewpoint, the basic components of a sustainable agroecosystem which will enhance these functions include:

1. Vegetative cover as an effective soil and water-conserving measure, met through the use of no-till practices, mulch farming, use of cover crops, and so forth
2. Regular supply of organic matter through regular addition of organic matter (manure, compost) and promotion of soil biotic activity
3. Nutrient recycling mechanisms through the use of crop rotations, crop/livestock mixed systems, agroforestry and intercropping systems based on legumes, and so forth
4. Pest regulation ensured through enhanced activity of biological control agents achieved through biodiversity manipulations and by introducing and/or conserving natural enemies

The basic concepts of a self-sustaining, low-input, diversified and efficient agricultural system must be synthesized into practical alternative systems to suit the specific needs of farming communities in different agroecological regions of the world. A major strategy in sustainable agriculture is to restore agricultural diversity in time and space through crop rotations, cover crops, intercropping, crop/livestock mixtures, and so on. (Altieri 1987). As seen in Figure 5.2, different options to diversify cropping systems are available depending on whether the current monoculture systems to be modified are based on annual or perennial crops. Diversification can also take place outside of the farm, for example, in crop-field boundaries with windbreaks, shelterbelts, and living fences, which can improve habitat for wildlife and beneficial insects, provide sources of wood, organic matter, resources for pollinating bees, and, in addition, modify wind speed and the microclimate (Altieri and Letourneau 1982).

There are many alternative diversification strategies that exhibit beneficial effects on soil fertility, crop protection, and crop yields. If one or more of these alternative technologies are used, the possibilities of complementing
Diversified in time and space
Dynamically stable
Productive and food self-sufficient

OBJECTIVES
Conservation and regeneration of natural resources (water, soil, nutrients) germplasm
Economic potential
Socially and culturally acceptable technology
Self-promoting and self-help potential

MODEL SUSTAINABLE AGROECOSYSTEM

Soil cover
Nutrient recycling
Sediment capture
Water harvest and conservation
Productive diversity
Crop protection
Ecological "order"

PROCESSSES

Crop Systems:
- polycultures
- fallow rotation
- crop densities
- mulching
- cover cropping
- no tillage
- selective weeding

Polycultures:
- use of residues
- rotation with legumes
- zonation of production
- improved fallow
- manuring
- alley cropping

Living and non-living barriers:
- selective weeding
- terracing
- no tillage
- zonation
- contour planting

METHODS
Regional Diversity:
- forest enrichment
- crop zonation
- crop mosaics
- windbreaks, shelterbelts

Genetic Diversity:
- species diversity
- cultural control
- biological control

Diversity Within the Agroecosystem:
- polycultures
- agroforestry
- crop-livestock association
- variety mixtures

Agroecosystem design and reorganization:
- mimicking natural succession
- agroecosystem analysis methodologies

FIGURE 5.1 Objectives and processes in the design of a model sustainable agroecosystem.
FIGURE 5.2 Diversification options for annual or perennial crop based cropping systems in California.
interactions between agroecosystems components are enhanced (Figure 5.3) resulting in one or more of the following effects:

1. Continuous vegetation cover for soil protection
2. Constant production of food, ensuring a varied diet and marketing items
3. Closing of nutrient cycles and effective use of local resources
4. Soil and water conservation through mulching and wind protection
5. Enhanced biological pest control through diversification
6. Increased multiple use capacity of the landscape
7. Sustained crop production without use of environmentally degrading chemical inputs

Sustainability can best be achieved through an understanding of the four subsystems of agriculture (Raeburn 1984):

1. Biological: plants and animals and the biological effects of physical and chemical factors (climate, soil) and of management activities (irrigation, fertilization, tillage) on plant and animal performance
2. Work: the physical tasks of agriculture and how they can be achieved by combining labor, skills, machinery, and energy
3. Farm economics: the cost of production and the prices of crops being raised, quantities produced and used, risks, and all other determinants of farm income
4. Socioeconomic: markets for farm products, land use rights, labor, machinery, fuel, inputs, credit, taxation, research, and technical assistance

The study of such subsystems is facilitated by the agroecological approach, which provides a conceptual framework to study the interactions within and between subsystems. Such interactions can be studied at any level. An advantage of the framework is that humans can be studied as integral components of agroecosystems.

Models for Agroecosystem Design

The physiological limits of crops, the carrying capacity of the habitat, and the external costs of enhancing production put a ceiling on potential productivity. This point is the management equilibrium (Lewis 1959) at which the ecosystem, in dynamic equilibrium with environmental and management factors, produces a sustained yield. The characteristics of this equilibrium will vary with different crops, geographical areas, and management objectives, so they will be highly site-specific. However, general guidelines for designing balanced and well-adapted cropping systems may be gleaned from the study of structural and functional features of the natural or seminatural ecosystem remaining in the area where agriculture is being practiced. Four major sources of "natural" information can be explored:
FIGURE 5.3 Complementary interactions in diversified cropping systems resulting in enhanced soil protection, soil fertility, and biological protection.
**Primary Production.** Depending on climatic and edaphic factors, each area is characterized by a type of vegetation with a specific production capacity. A natural grassland area (with a standing crop value of 6,600 g/m²) is not able to support a forest with a biomass of 26,000 grams per square meter) unless subsidies are added to the system. It follows then, that if a natural grassland needs to be transformed into an agricultural system, it should be replaced by cereals rather than orchards.

**Land Use Capability.** Soils have been classified into eight land use capability groups, each determined by physiochemical factors, such as slope or water availability (Vink 1975). According to this classification, soils of classes I and II are highly fertile, have good texture and permeability, and are deep and erosion-resistant; in short, they are suitable for many types of crops. However, when trees and shrubs are replaced by wheat on hillsides (i.e., class VI soil), yields decline progressively and the soil becomes badly eroded (Gasto and Gasto 1970). In determining the suitability of a tract of land for a certain agricultural use, it is important to consider qualities such as availability of water, nutrients, and oxygen; soil texture and depth; salinization and/or alkalinization; possibilities for mechanization; and resistance to erosion (Vink 1975). Figure 5.4 shows the relationship between USDA land capability classes and the intensity with which each class can be used safely.

**Vegetational Patterns.** The vegetation of a natural ecosystem can be used as an architectural and botanical model for designing and structuring an

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**FIGURE 5.4** Relationship between land capability classification classes and the intensity with which each class can be used (Vink 1975).
agroecosystem to replace it. The study of productivity, species composition, efficiency of resource use, resistance to pests, and leaf area distribution in natural plant communities is important for building agroecosystems that mimic the structure and function of natural successional ecosystems (Ewel 1986). Ewel argues that in the humid tropical lowlands, constructing forest-like agroecosystems that imitate successional vegetation is the only means for constructing a sustainable agriculture. Such agroecosystems would exhibit low requirements for fertilizer, high use of available nutrients, and high protection from pests.

This succession analog method requires a detailed description of a natural ecosystem in a specific environment and the botanical characterization of all potential crop components. When this information is available, the first step is to find crop plants that are structurally and functionally similar to the plants of the natural ecosystem. The spatial and chronological arrangement of the plants in the natural ecosystem are then used to design an analogous crop system (Hart 1978). In Costa Rica, Ewel et al. (1984) conducted spatial and temporal replacements of wild species by botanically/structurally/ecologically similar cultivars. Thus, successional members of the natural system such as Heliconia spp., cucurbitaceous vines, Ipomoea spp., legume vines, shrubs, grasses, and small trees were replaced by plantain, squash varieties, and yams. By years two and three, fast-growing tree crops (Brazil nuts, peach, palm, rosewood) may form an additional stratum, thus maintaining continuous crop cover, avoiding site degradation and nutrient leaching and providing crop yields throughout the year (Uhl and Murphy 1981).

Gasto (1980) designed a similar conversion system in the Mediterranean matorral (thicket) of central Chile. Matorral vegetation consists of shrubs (dominated by Acacia caven) and an understory of mixed grasses. Successful sheep pastures were developed by replacing the natural shrub layer with Atriplex spp. shrub, a food source for the animals. Thus, species composition was altered, but the structural profile was left intact.

Based on the concept that successful agricultural mimics of various ecosystems can be designed, Soule and Piper (1992) propose the prairie of the Great Plains as an appropriate natural model for grass seed agriculture. As opposed to the monocultures of annual crops—namely, corn, wheat, sorghum, and soybeans—that presently occupy most of the prairie soils, an agroecosystem modeled on the prairie would be dominated by mixtures of perennial grasses, legumes, and composites as seed crops, whose species composition would vary across soil type and climate. Polycultures of herbaceous perennial seed crops, based on the prairie community as a model, would be composed of plants that differ in seasonal nutrient use and would thereby play complementary and facilitating roles in the field. Promising candidates for such a perennial agriculture include the C₃ grasses
wild rye, or leymus (*Leymus racemosus*) and intermediate wheatgrass (*Agropyron intermedium*), the C\textsubscript{4} eastern gamagrass (*Tripsacum dactyloides*), the legume, Illinois bundleflower (*Desmanthus illinoensis*), and the Maximilian sunflower (*Helianthus maximilianii*), a composite.

Potentially, such an agriculture would utilize many of the sustainable features of the prairie. The use of perennial species would tap the prairie’s soil-retaining, soil-building aspects. The legume component would help maintain an internal fertility supply. The variety of climatic adaptations and seasonal variation in growth and reproduction would lend resiliency and promote efficient use of available resources. A diversity of crop species, including some native species, would allow development of natural checks and balances of herbivores, diseases, and weeds.

The broader implications of a grain agriculture based on perennial crops are conservation of natural resources, reform of the current economic system to be more ecologically based, and a society that engages nature on nature’s terms. An ecology-based economic system would take into account available ecological capital and feature steady states of resource cycling, efficient energy transfer, and reliance on available solar or biological energy.

By combining these expected sustainable features with the broader implications for society and the environment, a list of potential agricultural benefits of perennial polycultures one can formulate: (1) reduced or eliminated soil erosion, (2) efficient use of land area and soil nutrients, (3) increased water-use efficiency, (4) reduced reliance on industrially produced fertilizers, (5) decreases in pest and disease epidemics, (6) effective chemical-free weed management, (7) reduced energy use in tillage, (8) reduced chemical contamination of soil and water, and (9) insurance against complete crop failures.

*Knowledge of Local Farming Practices*

In most rural areas, farmers have been cultivating for decades. Some have failed and others have succeeded in developing cropping systems adapted to local conditions (Chapter 6). Despite the onrush of modernization and economic change, a few traditional agricultural management systems survive. These systems exhibit important elements of sustainability; namely, they are well adapted to their environment, rely on local resources, are small-scale and decentralized, and conserve natural resources. At the field level, traditional polycultures often parallel natural plant communities by containing:

- Genetic diversity in plant species
- Complex trophic relationships among crops, weeds, insects, and pathogens
• Relatively closed nutrient cycles, with many crop nutrient requirements supplied by rotations, fallow or manure
• Year-round vegetative cover of soil
• Efficient use of water, sunlight, and soil
• Low risk of complete loss of crops, due to diversity
• High level of production stability, due to compensation by the various components when one component fails

Thus, although tropical small farmers with little capital or institutional support have been confined to farming low quality, marginal soils, their systems provide valuable information for the development of yield-sustaining systems.

Choosing a Cropping System

Crop production systems include both cropping systems and the associated crop production practices and technologies used to raise crops. Cropping systems may consist of a monoculture of one continuous crop or formal sequences of crops repeated in an orderly pattern to constitute a rotation. They may also include flexible arrangements of one or more crops in time and space (intercropping, relay cropping), and intensive successions of crops within single years or even within seasons. Cropping systems vary greatly with differences in soil and climate and with local economic and social systems.

Crop growth and performance are subject to environmental conditions (topography, rainfall, soil texture and fertility) and management conditions (planting time, weeding). Before designing new cropping systems in an area already being farmed, the existing systems must be described in terms of rainfall and temperature (Beets 1982). A useful start is a simple climatic diagram with the months on the X axis and the average temperature (degrees Celsius) on the left side of the Y axis and the average precipitation (mm) on the right side of the Y axis, maintaining the relationship of one degree Celsius to 2 mm of precipitation. This relationship roughly approximates evaporation; when the precipitation curve is below that of the temperature curve, it denotes a period of drought. When precipitation is above temperature, there is enough moisture for crop growth. Thus, in the Central Plateau of Mexico, an analysis of this diagram (Figure 5.5) depicts four periods of great agronomic importance:

1. Low risk of frost at the end of spring
2. Beginning of rains
3. Average growing period
4. First autumn frosts
Several agronomic considerations are involved in developing a cropping system (Thorne and Thorne 1979). Cropping systems should be devised to provide high photosynthetic capabilities for as much of the year as is practical. In intercropped or mixed crops, plant height, the shape and angle of leaves, the rate of growth, and time period required to reach maturity are important characteristics that determine photosynthetic efficiency. There are several ways to combine crop plants to maximize solar radiation, such as by combining species of different phenologies, that reach maximum photosynthesis at different radiation levels, or that have roots that exploit different parts of the soil.
A major goal should be to maximize annual crop production or net economic gains per unit area of land. Thus, two short-season crops may provide greater total yields than one long-season crop. Decisions as to crop intensities must be based on the best available evidence for each combination of conditions. To promote sustained high yields and profits, cropping systems should be designed to maintain soil organic matter and tilth; to reduce the incidence of weeds, insects, and diseases; to help keep plant nutrients in balance; to conserve water; and to minimize soil erosion.

To use water and nutrients effectively, roots should form an active and extensive network throughout the soil. Good crop combinations have compatible root systems that permeate the soil to a depth of 25 to 30 cm with some roots extending much deeper.

**Crop Characteristics and Cropping Patterns**

Biological and agronomic characteristics of crop plants are important in selecting crops for any given situation and in determining appropriate farming practices. These characteristics are summarized as follows (Thorne and Thorne 1979):

**Growing Period.** The number of days required between date of plant emergence and maturity is important both in determining the correct climatic zone for a specific crop and in fitting a particular cultivar into a multiple cropping system.

**Photoperiodism.** For many plants, the length of night (darkness) rather than length of daylight is critical to initiate flowering, tillering, or dormancy. Short-day plants require prolonged daily darkness to induce flowering, and long-day plants initiate flowering when nights are relatively short. Some plants are day-neutral and develop without regard to day length. In some plants, the change in day length may be important to induce changes in development. Increasing day length may help initiate flowering, while, in the fall, the advent of shorter days may promote fruiting, maturity, or dormancy.

**Growth Habits.** The growth habits of crop plants are important in determining production and management practices. Dwarf varieties are generally preferred over tall varieties because of their upright growth habit, greater ease of harvesting by machine, reduced likelihood of lodging, earlier fruiting, and frequently higher harvest index. Bush varieties are preferred over vines because they have many branches that bear fruit uniformly.

**Root Systems.** Two types of root systems are common to crop plants: fibrous roots and tap roots. Fibrous roots permeate the soil and hold soil particles together. Grasses, for example, promote good soil structure and help protect soils against erosion. Tap-rooted crops are those with roots commonly harvested for food or feed, such as sugar beets, mangels, carrots, and turnips. Tap-rooted plants tend to be deep-rooted, such as alfalfa and
trees. Deep-rooted plants maximize the upward flow of both soluble and less soluble nutrients.

In most crop plants, the major volume of roots is in the upper 30 cm of soil. The depth of intensive rooting is affected by soil moisture, texture, compaction, aeration, and the supply of available plant nutrients.

The Design of a Sustainable Agroecosystem

Diversification of an Onion Field in Michigan

Few researchers have been able to gather sufficient information on the forms of cultural and biological control applicable to specific crop pests of known biology in order to advance a series of environmental management proposals to improve the control of insect pests affecting specific crops. An exception is the work of Groden (1982) in Michigan who designed a functionally diverse onion agroecosystem to optimize the mortality of the major onion insect pest, the onion maggot (Delia antiqua). This design was derived from quantitative models describing the relationships among components in the system. From an understanding of these quantitative interactions, designs incorporating diseases, weeds, insects, and so forth, can be derived as long as the relationships that are used in the construction of these "free-body" models are structure independent or incorporate aspects of structure as a variable.

The alternative design of the onion agroecosystem shown in Figure 5.6 stresses planned or functional diversity. The cow pasture and weedy borders provide alternate host and nectar for the onion maggot parasite, A. pallipes (Groden 1982). The cow pasture also provides a rich resource for earthworms, thereby potentially maximizing the densities of the tiger fly predator of onion flies. The long, narrow strips of onions minimize the distance between any point in the onion field, weedy borders and cow pasture. This is important since A. pallipes numbers decline exponentially from weedy borders and cow pastures into the onion field (Groden, 1982). This is also true of onion flies infected with disease caused by Entomophthora muscae. Weedy field borders are not mowed so that attachment sites for diseased flies are provided. Narrow weedy borders maximize the probability of E. muscae spores encountering healthy flies by crowding together resting and attachment sites for healthy flies during midday. By mowing some of the weedy border, this crowding effect can be increased. The planting of radishes adjacent to onions provides an alternate host and thus a continuous food supply for the rove beetle, A. bilineata. A number of plantings should be used in order to provide a season-long food resource or the cabbage maggot and a number of different planting dates of onions should be incorporated into the design (Groden 1982). Groden also showed
FIGURE 5.6 Sustainable agriculture planting for minimizing the impact of onion maggot and the need for the use of insecticides for control of this pest (after Groden 1982).

that early planted onions adjacent to late planted onions serve as a highly attractive trap crop resulting in a concentration of the onion maggot population in the early planting. Because the later plantings go largely untouched, the early planting can be positioned near the radish interface so that the host pool for *A. bilineata* is concentrated, thereby making prey search more efficient.

In order to deal with the problem of emerging flies after onions are harvested, management of cull onions becomes a major issue. A diversification management option involves sowing a fall rye or oat cover crop immediately after harvest so that in a week the cover crop hides the cull onions in the field, making it difficult for the onion flies to find the culls. A modification is not to harvest a small section of onion rows, and then, while sowing the cover crop, the tops of the onions can be cut off and left on the ground. The cut tops are more attractive to the onion flies than the cull onions and the onion fly immatures cannot survive on them because they dry up before insect development is completed. Thus, the cut tops serve to keep
the onion flies from laying on the culls until the cover crop comes up, and then the searching efficiency of the female flies is drastically reduced. In addition, crop rotation significantly reduces the number of flies colonizing an onion field in the spring (Mortinson et al. 1988).

**Ecological Guidelines for Agroecosystem Design and Management**

According to Reijintjes et al. (1992), there are five ecological principals basic to the design and management of sustainable agroecosystems:

1. Securing favorable soil conditions for plant growth, particularly by managing organic matter and enhancing soil life
2. Optimizing nutrient availability and balancing nutrient flow, particularly by means of nitrogen fixation, nutrient pumping, recycling and complementary use of external fertilizers
3. Minimizing losses due to flows of solar radiation, air, and water by way of microclimate management, water management and erosion control
4. Minimizing losses due to plant and animal pests and diseases by means of prevention and safe treatment
5. Exploiting complementarily and synergy in the use of genetic resources, which involves combining these in integrated farm systems with a high degree of functional diversity

These principles can be applied by way of various techniques and strategies. Each of these will have different effects on productivity, security, continuity, and identity within the farm system, depending on the local opportunities and limitations (above all, resource constraints) and, in most cases, on the market.

The degree to which agroecosystems increase in ecological sustainability, particularly in a fragile soil environment, depends largely on the following six biologically based principles (NRC 1993):

1. The degree to which nutrients are recycled. Productivity within a system is directly related to the magnitude of nutrient mobilization and flow. Sustainability is directly related to the magnitude of nutrient use and to the reduction of nutrient loss.
2. The extent of which the soil surface is physically protected. Soil loss through water transport or wind erosion must be minimized. It should be protected from oxidation or other chemical deterioration through protective plant cover. Physical deterioration, compaction, and loss of structure through rainfall can be equally damaging, reducing productive potential. Continuous crop or crop residue cover from appropriately managed systems is crucial to maintenance of productive potential.
3. The efficiency and degree of utilization of sunlight, soil, and water resources. Selected agricultural systems must be managed for optimal use, including continuous crop cover, good crop, and animal genetic potential, minimal pest damage, and optimal nutrient supply.

4. A small offtake (harvested removal) of nutrients in relation to total biomass. Where soils are erosive, have poor nutrient status, or are otherwise chemically or physically fragile, the maintenance of high biomass systems is critical.

5. Maintenance of a high residual biomass in the form of wood, herbaceous material, or soil organic material. A carbon source for both energy and nutrient retention is critical to the support of biomass in the soil and to crop and animal productivity.

6. The structure and preservation of biodiversity. The efficiency of nutrient cycling and the stability of pests and diseases in the system depend on the amount and type of biodiversity as well as its temporal and spatial arrangement (structural diversity). Traditional systems, particularly those in marginal production environments, often have significant stability and resiliency as a result of high structural diversity.
About 60 percent of the world's cultivated land is still farmed by traditional and subsistence methods (Ruthenberg 1971). This type of agriculture has benefitted from centuries of cultural and biological evolution that has adapted it to local conditions (Egger 1981). Thus, small farmers have developed and/or inherited complex farming systems that have helped them meet their subsistence needs for centuries, even under adverse environmental conditions (on marginal soils, in drought or flood-prone areas, with scarce resources) without depending on mechanization or chemical fertilizers and pesticides. Generally these farming systems consist of a combination of production and consumption activities (Figure 6.1).

Most small farmers have employed practices designed to optimize productivity in the long term rather than maximize it in the short term (Gliessman et al. 1981). Inputs characteristically originate in the immediate region and farm work is performed by humans or animals that are fueled from local sources (Figure 6.2). Working within these energy and spatial constraints, small farmers have learned to recognize and use locally available resources (Wilken 1977). Traditional farmers are much more innovative than many agriculturalists believe. In fact, most productivity comparisons between Green Revolution and traditional agriculture systems have been biased and unfair, as they ignore the fact that traditional farmers value total farming system production and not just yields of one commodity as it is the case in a Green Revolution system (Figure 6.3). Many scientists in developed countries are beginning to show interest in traditional agriculture, especially in small-scale mixed crop systems, as they search for ways to remedy deficiencies in modern agriculture. This transfer of learning must occur rapidly, however, or this wealth of practical knowledge will be lost forever.
FIGURE 6.1 Scheme of a small farming system with four production/consumption systems (Zandstra et al. 1981).

FIGURE 6.2. Conceptual model of the production system of a Nepalese hill farm (Harwood 1979a).

Ecological Features of Traditional Agriculture

As more research is conducted, many farming practices once regarded as primitive or misguided are being recognized as sophisticated and appropriate. Confronted with specific problems of slope, flooding, droughts, pests, diseases, and low soil fertility, small farmers throughout the world have developed unique management systems to overcome these constraints (Table 6.1). Traditional agriculturalists generally have met the environmental requirements of their food-producing systems by concentrating on a few principles and processes (Knight 1980):

**Spatial and Temporal Diversity and Continuity.** Multiple cropping designs are adopted to ensure constant food production and vegetation cover for soil protection. By ensuring a regular and varied food supply, a diverse and nutritionally adequate diet is assured. Extended crop harvest reduces the necessity for storage, often hazardous in rainy climates.
MIXED FARMING
SYSTEM

DIVERSE CROPS OF
CEREALS, PULSES,
MILLETS, OIL SEEDS

REDUCED TO

PART OF CROP PC₁
(GRAIN)

GREEN REVOLUTION
MONOCULTURE

CEREAL CROPS OF WHEAT
OR RICE

REDUCED TO

PART OF CROP PC₂
(GRAIN)

THE REAL SCIENTIFIC COMPARISON SHOULD BE BETWEEN TWO FARMING
SYSTEMS—FS₁ AND FS₂ WITH THE FULL RANGE OF INPUTS AND OUTPUTS
INCLUDED.

THIS WOULD BE THE COMPARISON IF FS WAS NOT GIVEN IMMUNITY FROM
AND ECOLOGICAL EVALUATION.

IN THE GREEN REVOLUTION STRATEGY, A FALSE COMPARISON IS MADE
BETWEEN PC₁ AND PC₂.

SO WHILE PC₂ > PC₁ GENERALLY FS₁ > FS₂.

FIGURE 6.3 Unfair comparisons between Green Revolution and traditional agri-
cultural systems.
### TABLE 6.1 Some examples of soil, space, water, and vegetation management systems used by traditional agriculturalists throughout the world (after Klee 1980).

<table>
<thead>
<tr>
<th>ENVIRONMENTAL CHARACTERISTIC</th>
<th>OBJECTIVE</th>
<th>RECOMMENDED PRACTICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited space</td>
<td>Maximize use of environmental resources and land</td>
<td>Intercropping, agroforestry, multi-story cropping, home gardens, altitudinal crop zonation, farm fragmentation, rotation</td>
</tr>
<tr>
<td>Steep slopes</td>
<td>Control erosion and conserve water</td>
<td>Terracing, contour farming, living and dead barriers, mulching, leveling, continuous crop and/or fallow cover, stone walls</td>
</tr>
<tr>
<td>Marginal soil fertility</td>
<td>Sustain soil fertility and recycle organic matter</td>
<td>Natural or improved fallow, crop rotations and intercropping with legumes, litter gathering, composting, manuring, green manuring, grazing animals in fallow fields, night soil and household refuse, mounding with hoe, ant hills as source of fertilizer, use of alluvial deposits, use of aquatic weeds and muck, alley cropping with legumes, plowed leaves, branches and other debris, burning vegetation, and so on.</td>
</tr>
<tr>
<td>Flooding or excess water</td>
<td>Integrate agriculture with water supply</td>
<td>Raised field agriculture (chinampas, tablones), ditched fields, diking, and so on.</td>
</tr>
<tr>
<td>Excess water</td>
<td>Channel/direct available water</td>
<td>Control floodwater with canals and checkdams. Sunken fields dug down to groundwater level. Splash irrigation. Canal irrigation fed from ponded groundwater, wells, lakes, reservoir</td>
</tr>
</tbody>
</table>
### TABLE 6.1 continued.

<table>
<thead>
<tr>
<th>ENVIRONMENTAL CHARACTERISTIC</th>
<th>OBJECTIVE</th>
<th>RECOMMENDED PRACTICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreliable rainfall</td>
<td>Best use of available moisture</td>
<td>Use of drought-tolerant crop species and varieties, mulching, weather indicators, mixed cropping using end of rainy season, crops with short growing periods</td>
</tr>
<tr>
<td>Temperature or radiation extremes</td>
<td>Ameliorate microclimate</td>
<td>Shade reduction or enhancement; plant spacings; thinning; shade-tolerant crops; increased plant densities; mulching; wind management with hedges, fences, tree rows; weeding; shallow plowing; minimum tillage; intercropping; agroforestry; alley-cropping, and so on.</td>
</tr>
<tr>
<td>Pest incidence (invertebrates, vertebrates)</td>
<td>Protect crops, minimize pest populations</td>
<td>Overplanting, allowing some pest damage, crop watching, hedging or fencing, use of resistant varieties, mixed cropping, enhancement of natural enemies, hunting, picking, use of poisons, repellents, planting in times of low pest potential</td>
</tr>
</tbody>
</table>

A continuous sequence of crops also maintains biotic relationships (predator/prey complexes, nitrogen fixing) that may benefit the farmer.

**Optimal Use of Space and Resources.** Assemblages of plants with different growth habits, canopies, and root structures allows for better use of environmental inputs such as nutrients, water, and solar radiation. Crop mixtures make fullest use of a particular environment. In complex agroforestry systems, crops can be grown underneath tree canopies if enough light filters through.

**Recycling of Nutrients.** Small farmers sustain soil fertility by maintaining closed cycles of nutrients, energy, water, and wastes. Thus, many farmers enrich their soils by collecting nutrient materials (such as manure and forest litter) from outside their fields, adopting fallow or rotational systems, or including legumes in their intercropping patterns.
**Water Conservation.** In rainfed areas, the rainfall pattern is the main cropping system determinant, and farmers use cropping patterns adapted to the amount and distribution of rainfall. Thus, in areas with little moisture, farmers prefer drought-tolerant crops (like *Cajanus*, sweet potato, cassava, millet, and sorghum), and management techniques emphasize soil cover (such as mulching) to avoid evaporation and runoff. Where precipitation is more than 1,500 mm/year, most cropping systems are based on rice. Under constant flooding conditions, instead of investing in costly drainage systems, farmers develop integrated agriculture/aquaculture systems, such as the chinampas of Central Mexico.

**Control of Succession and Protection of Crops.** Farmers have developed a number of strategies to cope with competition from undesirable organisms. Crop species and variety mixtures provide insurance against catastrophic attacks from insect pests or disease. Crop canopies can effectively suppress weed growth and minimize the need for weed control. In addition, cultural practices such as mulching, changes in planting times and durability, use of resistant varieties, and use of botanical insecticides and/or repellents can minimize pest interference.

**Advantages of Crop Diversity**

Perhaps one of the most striking features of traditional farming systems in most developing countries is the degree of crop diversity both in time and space. This diversity is achieved through multiple cropping systems, or polycultures. For example, in the Latin American tropics, 60 percent of the corn is grown in association with other crops.

Polyculture is a traditional strategy to promote diet diversity income generation, production stability, minimization of risk, reduced insect and disease incidence, efficient use of labor, intensification of production with limited resources, and maximization of returns under low levels of technology (Francis et al. 1976, Harwood 1979a). Polyculture systems offer many advantages over the monoculture agriculture practiced in modern countries, as follows (Ruthenberg 1971, Altieri 1983, Francis 1986):

**Yields.** Total yields per hectare are often higher than sole-crop yields, even when yields of individual components are reduced. This yield advantage is usually expressed as the land equivalent ratio (LER), which expresses the monoculture land area required to produce the same amount as one hectare of polyculture, using the same plant population. If the LER is greater than one, the polyculture overyields. Most corn/bean dicultures and corn/bean/squash tricultures studied are examples of overyielding in polycultures.

**Efficient Use of Resources.** Mixtures result in more efficient use of light, water, and nutrients by plants of different height, canopy structure, and nutrient requirements. There is some indication that long-duration intercrop
combinations have an advantage over monocultures when nutrients are limited. Thus, in polycultures combining perennial and annual crops, the minerals lost by annuals are rapidly taken up by perennials. On the other hand, the nutrient-robbing propensity of some crops is counteracted by the enriching addition of organic matter to the soil by other crops (like legumes) in the mixture.

**Nitrogen Availability.** In cereal/legume mixtures, fixed nitrogen from legumes is available to the cereal, thereby improving the nutritional quality. Corn and beans complement each other in essential amino acids.

**Reduction of Diseases and Pests.** Diseases and pests may not spread as rapidly in mixtures because of differential susceptibility to the pests and pathogens and because of enhanced abundance and efficiency of natural enemies. In Southeast Asia, for example, maize grown in rows two and three meters apart, intercropped with soybeans, groundnuts, upland rice, or mung beans suffers relatively little from downy mildew, normally a major maize disease. Similarly, in Costa Rica, cowpea mosaic and chlorotic viruses occurred at lower levels in cowpea intercropped with cassava than in cowpea monocultures (Altieri and Liebman 1986). Diversified crop systems can increase opportunities for natural enemies and consequently improve biological pest control. Two-thirds of the studies dealing with the effects of crop diversity on insect pests showed that pestiferous insects decreased in the diversified system when compared with the corresponding monoculture. In many cases this was due to the abundance and efficiency of natural enemies. Cabbage aphids, flea beetles, diamondback moths, and corn earworms, are all insect pests that can be regulated with specific crop mixes (Altieri and Letourneau 1982).

**Weed Suppression.** The shading provided by complex crop canopies helps to suppress weeds, thereby reducing the need and cost of weed control. In the Philippines, shade-sensitive weeds such as nutsedge and *Imperata cylindrica* may be eliminated entirely by a combination like maize/mungbean, which intercepts 90 percent of the light after 50 days of growth.

**Insurance Against Crop Failure.** Polycultures provide insurance against crop failure, especially in areas subject to frosts, floods, or droughts. Thus, when one crop in a combination is damaged early in the growing season, the other crops may compensate for the loss. For example, in the highlands of Tlaxcala, Mexico, farmers intercrop corn with fava beans because fava beans survive frosts, whereas corn does not.

**Other Advantages.** Polycultures provide effective soil cover and reduce the loss of soil moisture. They enhance opportunities for marketing, ensuring a steady supply of a range of products without much investment in storage, thus increasing the marketing success. Mixtures spread labor costs more evenly throughout the cropping season and usually give higher gross returns per unit of labor employed, especially during periods of labor scarcity.
Polycultures also improve the local diet; 500 grams of maize and 100 grams of black beans per day provide about 2,118 calories and 68 grams of protein.

The Nature of Traditional Farming Knowledge

The terms traditional knowledge, indigenous technical knowledge, rural knowledge, and ethnoscience (or people's science) have been used interchangeably to describe the knowledge system of an ethnic rural group that has originated locally and naturally. This knowledge has many dimensions, including linguistics, botany, zoology, craft skills, and agriculture and is derived from the direct interaction between humans and the environment. Information is extracted from the environment by special cognition and perception systems that select for the mostly adaptive or useful information, and successful adaptations are preserved and passed on from generation to generation through oral or experiential means. Only recently has some of this knowledge been described and written down by researchers. Evidence suggests that the finest discrimination evolves (1) from communities where the environments have great physical and biological diversity and/or (2) in communities living near the margins of survival (Chambers 1983). Also, older members of the communities possess greater, more detailed knowledge than younger members.

For agroecologists, several aspects of these traditional knowledge systems are relevant:

1. Knowledge about the physical environment (soils, climate, etc.)
2. Biological folk taxonomies (or classification systems)
3. The experimental nature of this traditional knowledge

Indigenous people's knowledge about soils, climates, vegetation, animals, and ecosystems usually results in multidimensional productive strategies (i.e., multiple ecosystems with multiple species), and these strategies generate (within certain ecological and technical limits) the food self-sufficiency of farmers in the region (Toledo et al. 1985).

Knowledge About the Environment

Indigenous knowledge about the physical environment is often very detailed. Many farmers throughout the world have developed traditional calendars to control the scheduling of agricultural activities. In east Africa, for example, many farmers sow according to the phase of the moon, believing that there are lunar phases of rainfall. Many farmers also cope with climatic seasonality by utilizing weather indicators based on the phenologies of local vegetation. For example, in West Java, Gadung, sp. is a weather
indicator because the rainy season can be expected to begin shortly after its leaves start to grow. In the same region, pomelo has a similar function. When its fruits start to grow, the season of annual plant cultivation begins (Christiany et al. 1985).

**Soil Classification Systems and Use**

Soil types, degrees of soil fertility, and land-use categories are also discriminated in detail by farmers. Soil types are usually distinguished by color, texture, and even taste. Shifting cultivators usually classify their soils based on vegetation cover. In general, peasant soil classification types are dependent on the nature of the peasant’s relationship to the land (Williams and Ortiz Solorio 1981). Aztec soil classification systems were very complex, recognizing more than two dozen soil types identified by source of origin, color, texture, smell, consistency, and organic content. These soils were also ranked according to agricultural potential and used in both land value evaluations and rural census. Andean peasants in Coporaque, Peru, recognize four main soil classes. Each soil class has specific characteristics that define the most adequate cropping system (McCamant 1986). Examples of rurally developed land/soil categories can be found in Chambers (1983).

**Biological Folk Taxonomies**

Many complex systems used by indigenous people to group together plants and animals have been documented (Berlin et al. 1973). In general, the traditional name of a plant or animal usually reveals that organism's taxonomic status. Researchers have found that, in general, there is a good correlation between folk taxa and scientific taxa. Classification of animals, especially insects and birds, is widespread among farmers and indigenous groups (Bulmer 1965). Insects and related arthropods have major roles as crop pests, as causes of disease, as food, and as medicinals and are important in myth and folklore. In many regions, agricultural pests are tolerated because they also constitute agricultural products; that is, indigenous people may consume plants and animals that would otherwise be considered pests. In Indonesia, a grasshopper pest in rice is trapped at night and eaten (with salt, sugar, and onions) or sold as bird food in the market. The major bird pest in Indonesian rice fields (*Lonchura*) is caught in spring-loaded traps and eaten. Squirrels and termites, both of which damage crops, are also consumed. Shifting cultivars in Borneo trap and eat wild pigs that are attracted to their crops. In northeast Thailand, rural inhabitants eat rats, termites, and a crab that damages rice stalks (Brown and Marten 1986).

Ants, some major crop pests, are one of the most popular insect foods, gathered in tropical regions. In his studies of the ethnoentomology of the
Brazilian Amazon, Posey (1986) described the Indians' detailed knowledge of insect life cycles, uses, and management. The complex management of stingless bees (Meliponinae) for honey production illustrates a deep ecological knowledge of their biology. The role of social insects as "natural models" for the Kayapo Indians is especially interesting; insect behaviors are symbolically recognized in rituals and ceremonies (Posey 1986).

**Traditional Ethnobotanical Knowledge**

Ethnobotanies are the most commonly documented folk taxonomies. The ethnobotanical knowledge of certain campesinos in Mexico is so elaborate that the Tzeltals, P'urepechas, and Yucatan's Mayans recognize more than 1,200, 900, and 500 plant species respectively (Toledo et al. 1985). Similarly !Ko bushwomen in Botswana could identify 206 out of 266 plants collected by researchers (Chambers 1983), and Hanunoo swidden cultivators in the Philippines can distinguish more than 1,600 plant species (Conklin 1979).

Polycultures and agroforestry patterns are not developed at random; rather, they are based on a deep understanding of agricultural interactions guided by complex ethnobotanical classification systems. These classification systems have allowed peasants to assign each landscape unit a given productive practice, thus obtaining a diversity of plant products through a multiple-use strategy (Toledo et al. 1985). In Mexico, for example, Huastec Indians manage a number of agricultural and fallow fields, complex home gardens, and forest plots, totalling about 300 plant species. Small areas around the houses commonly average 80 to 125 useful plants, mostly native medicinal plants (Alcorn 1984). Similarly, the traditional Pekarangan in West Java commonly contains about 100 or more plant species. Of these plants about 42 percent provide building materials and fuelwood, 18 percent are fruit trees, 14 percent are vegetables and the reminder constitute ornamentals, medicinal plants, spices, and cash crops (Christian ty et al. 1985).

**The Experimental Nature of Traditional Knowledge**

The strength of rural people's knowledge is that it is based not only on acute observation but also on experimental learning. The experimental approach is very apparent in the selection of seed varieties for specific environments, but it is also implicit in the testing of new cultivation methods to overcome particular biological or socioeconomic constraints. In fact, Chambers (1983) argues that farmers often achieve a richness of observation and a fineness of discrimination that would be accessible to western scientists only through long and detailed measurement and computation.

In studying the variegated grasshopper (*Zonocerus variegatus*) in southern Nigeria, Richards (1985) found that the local farmers' knowledge was equivalent
to that of his scientific team concerning the grasshoppers' food habits, life cycle, mortality factors, and degree of damage to cassava and concerning the egg-laying behavior and egg-laying sites of the females. Local knowledge added facts to the researchers' data regarding the dates, severity, and geographic extent of some of the outbreaks, plus the fact that the grasshoppers were eaten and sold and were of special importance to women, children, and poor people. Thus, the final control recommendation by scientists, which was to clear the egg-laying sites from a block of farms, did not require most farmers to learn new concepts and for some the practice was nothing new.

Some Examples of Traditional Management Practices

Soil Fertility Management Practices

Indigenous farmers have developed various techniques to improve or maintain soil fertility. For example, farmers in Southern Sudan and Zaire noticed that the sites of termite mounds are particularly good for growing sorghum and cowpea (Reijntjes et al. 1992). Farmers in Oaxaca, Mexico, use *Atta* ant refuse to fertilize high-value crops such as tomatoes, chili, and onions (Wilken 1987).

In Quezaltenango, Guatemala, leaf litter is brought in large quantities from nearby forests to improve till and moisture retention of intensively worked vegetable plots. Use rates for leaf litter vary between 20–30 t/ha/yr. It is estimated that a hectare of mixed pine/oak forest produces about 4,000 kg of litter annually, thus a hectare of cropped land requires the litter production from 5–10 ha of forest (Wilken 1987).

In Senegal, the indigenous agrosilvopastoral system takes advantage of the multiple benefits provided by *Faidherbia* (formerly *Acacia*) *albida*. The tree sheds its leaves at the onset of the wet season, permitting enough light to penetrate for the growth of sorghum and millet, yet still providing enough shade to reduce the effects of intense heat. In the dry season, the tree's long tap roots draw nutrients from beyond the reach of other plants; the nutrients are stored in the fruits and leaves. The tree also fixes nitrogen from the air, thus enriching the soil and improving crop yields. In the wet season, the fallen leaves provide mulch that enriches the topsoil as well as highly nutritious forage. The soil is also enriched by the dung of livestock, which feed on the *F. albida* leaves and the residues of the cereal crop (Reijntjes et al. 1992).

Microclimate Management Practices

Farmers influence microclimate by retaining and planting trees, which reduce temperature, wind velocity, evaporation, and direct exposure to
sunlight and intercept hail and rain. They apply mulches of ground-covering plants or straw to reduce radiation and heat levels on newly planted surfaces, inhibit moisture losses, and absorb the kinetic energy of falling rain and hail. When night frost is expected, some farmers burn straw or other waste materials to generate heat and produce smog, which traps outgoing radiation. The raised planting beds, mounds, and ridges often found in traditional systems serve to control soil temperatures and to reduce waterlogging by improving drainage (Wilken 1987; Stigter 1984).

**Indigenous Insect Pest Control Methods**

Traditional farmers rely on a variety of management practices to deal with agricultural insect pest problems. Two main strategies can be distinguished. One is the use of direct, non-chemical pest control methods (i.e., cultural, mechanical, physical, and biological practices) (Table 6.2). The second is reliance on built-in pest control mechanisms, inherent to the biotic and structural diversity of complex farming systems, commonly used by traditional farmers (Brown and Marten 1986). This ensemble of cultural practices can be grouped into three main strategies, depending on which element of the agroecosystem is manipulated.

**Manipulation of Crops in Time.** Farmers often manipulate the timing of planting and harvest carefully and use crop rotations to avoid pests. These techniques obviously require considerable ecological knowledge of pest phenology. Although these techniques often have other agronomic benefits (e.g., improved soil fertility), the farmers sometimes explicitly mention that they are done to avoid pest damage. For example in Uganda, farmers utilize time of planting to avoid stem borers and aphids in cereals and peas, respectively (Richards 1985). Many farmers are aware that planting out of synchrony with neighboring fields can result in heavy pest pressure and therefore use a kind of "pest satiation" to avoid extensive damage. In the central Andes, a potato fallow rotation is carefully observed, apparently to avoid buildup of certain insects and nematodes (Brush 1982).

**Manipulation of Crops in Space.** Traditional farmers often manipulate plot size, plot site location, density of crops and crop diversity to achieve several purposes, although most are aware of the links between such practices and pest control (Altieri 1993a).

1. Overplanting. One of the most common methods of dealing with pests is planting at a higher density than one expects to harvest. This strategy is most effective in dealing with pests that attack the plant during the early stages of growth. When infested plants are detected, they are carefully removed long before actual death to avoid contaminating healthy plants.
TABLE 6.2 Pest management strategies and specific practices used by traditional farmers throughout the developing world.

<table>
<thead>
<tr>
<th>STRATEGY</th>
<th>PRACTICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical and physical control</td>
<td>Scarecrows, sound devices&lt;br&gt;Wrapping of fruits, pods&lt;br&gt;Painting stems, trunks with lime or other materials&lt;br&gt;Destroying ant nests&lt;br&gt;Digging out eggs/larvae&lt;br&gt;Hand picking&lt;br&gt;Removal of infested plants&lt;br&gt;Selective pruning&lt;br&gt;Application of materials (ash, smoke, salt, etc.)&lt;br&gt;Burning vegetation</td>
</tr>
<tr>
<td>Cultural practices</td>
<td>Intercropping&lt;br&gt;Overplanting or varying seeding rates&lt;br&gt;Changing planting dates&lt;br&gt;Crop rotation&lt;br&gt;Timing of harvest&lt;br&gt;Mixing crop varieties&lt;br&gt;Selective weeding&lt;br&gt;Use of resistant varieties&lt;br&gt;Fertilizer management&lt;br&gt;Water management&lt;br&gt;Plowing and cultivation techniques</td>
</tr>
<tr>
<td>Biological control</td>
<td>Use of geese and ducks&lt;br&gt;Transfer of ant colonies&lt;br&gt;Collecting and/or rearing predators and parasites for field release&lt;br&gt;Manipulation of crop diversity</td>
</tr>
<tr>
<td>Insecticidal control</td>
<td>Use of botanical insecticides&lt;br&gt;Use of plants or plant parts as repellents and/or attractants&lt;br&gt;Use of chemical pesticides</td>
</tr>
<tr>
<td>Religious/ritual practices</td>
<td>Addressing spirits or gods&lt;br&gt;Placement of crosses or other objects in the field&lt;br&gt;Prohibition of planting dates</td>
</tr>
</tbody>
</table>

2. Farm plot location. In Nigeria many farmers, linked by kinship ties, age grouping, or friendship, locate their farm plots lying contiguous to each other but leaving room for the expansion of each farm in a particular direction. In accounting for this practice, farmers reported that all pests in the area will discover and concentrate on an isolated farm. Plots are therefore grouped together to spread pest risk among many farmers. Conversely, in tropical
America, Brush (1982) reports that farmers deliberately use small isolated plots to avoid pests.

3. Selective weeding. Studies conducted in traditional agroecosystems show that peasants deliberately leave weeds in association with crops by not completely clearing all weeds from their cropping system. This "relaxed" weeding is usually seen by agriculturalists as the consequence of a lack of labor and low return for the extra work, however, a closer look at farmer attitudes toward weeds reveals that certain weeds are managed and even encouraged if they serve a useful purpose. In the lowland tropics of Tabasco, Mexico, there is a unique classification of non-crops according to use potential on the one hand and effects on soil and crops on the other. According to this system, farmers recognized 21 plants in their cornfields classified as mal monte (bad weeds), and 20 as buen monte (good weeds) that serve, for example, as food and medicines, ceremonial materials, teas, and soil improvers (Chacon and Gliessman 1982).

Similarly, the Tarahumara Indians in the Mexican Sierras depend on edible weed seedlings (Amaranthus, Chenopodium, and Brassica) from April through July, a critical period before maize, bean, cucurbits, and chiles mature in the planted fields in August through October. Weeds also serve as alternate food supplies in seasons when the maize crops are destroyed by frequent hailstorms. In a sense the Tarahumara practice a double crop system of maize and weeds that allows for two harvests: one of weed seedlings or quelities early in the growing season (Bye 1981). Some of these practices have important insect pest control implications since many weed species play important roles in the biology of herbivorous insects and their natural enemies in agroecosystems. Certain weeds, for example, provide alternate food and/or shelter for natural enemies of insect pests during the crop season but, more importantly, during the off-season when prey/hosts are unavailable.

4. Manipulation of crop diversity. Although most farmers use intercropping mainly because of labor and land shortages or other agronomic purposes, the practice has obvious pest control effects (Altieri and Letourneau 1982). Many farmers know this and use polycultures as a play-safe strategy to prevent buildup of specific pests to unacceptable levels or to survive in cases of massive pest damage. For example, in Nigeria, farmers are aware of the severe damage done to an isolated cassava crop by the variegated grasshopper after all other crops have been harvested. To reduce this damage, farmers deliberately replant maize and random clusters of sorghum on the cassava plot until harvest time.

**Manipulation of Other Agroecosystem Components.** In addition to manipulating crop spatial and temporal diversity, farmers also manipulate other cropping system components such as soil, microclimate, crop genetics, and chemical environment to control pests.
1. Use of resistant varieties. Through both conscious and unconscious selection, farmers have developed crop varieties that are resistant to pests. This is probably the most widely used and effective of all the traditional methods of pest control. Litsinger et al. (1980) found that 73% of the peasant farmers in the Philippines were aware of varietal resistance even if they had not consciously tried to manipulate it. There is evidence in traditional varieties for all the modes of resistance that modern plant breeders select for, including pubescence, toughness, early ripening, plant defense chemistry, and vigor.

In Ecuador, Evans (1988) found that infestations of Lepidoptera larvae in ripening corn ears were significantly higher in new varieties than in traditional ones, a factor that influenced the adoption of new varieties by small farmers.

2. Water management. Manipulation of water level in rice fields is a practice widely used for pest control (King 1927). Water management is also practiced in many other annual crops for the same purpose. For example, in Malaysia, control of cutworms and army worms is effected by cutting off the tip of infested leaves in a number of annual crops and raising the water level, which carries the larvae into the field ridges, where birds congregate to eat them.

3. Plowing and cultivation techniques. Farmers frequently report that they deliberately manage the soil (sometimes using more and sometimes less cultivation) to destroy or avoid pest problems. In Peru, for example, peasants use high tilling of potatoes to protect the tubers from insect pests and disease (Brush 1983). In shifting cultivation, after clearing a piece of land farmers set it on fire after a week or two. Farmers reported that this is done, among other reasons, to reduce weeds and pest populations during the first year of cropping (Atteh 1984).

4. Use of repellents and/or attractants. Farmers have been experimenting with various natural materials found in their immediate environment (especially in plants) for many centuries, and a remarkable number have some pesticidal properties. Use of plant or plant parts either placed in the field or applied as herbal concoctions for pest inhibition is wide-spread. Litsinger et al. (1980) interviewed small farmers in the Philippines about materials used in the fields to attract or repel insects. In Alboburo, Ecuador, small farmers place castor leaves in recently planted corn fields to reduce populations of a nocturnal tenebrionid beetle. These beetles prefer castor leaves over corn, but when associated with castor leaves for 12 hectares or more, beetles exhibit paralysis. In the field, the paralysis prevents beetles from hiding in the soil, which increases their mortality by direct exposure to the sun (Evans 1988). In southern Chile, peasants placed branches of Cestrum parqui in potato fields to repel Epicauta pilme beetles (Altieri 1993a). Many times a plant is carefully grown near the household and its sole
function is apparently to provide the raw material for preparing a pesticidal concoction. In Tanzania, farmers cultivate *Tephrosin* spp. on the borders of their maize fields. The leaves are crushed and the liquid is applied to control maize pests. In Tlaxcala, Mexico, farmers "sponsor" volunteer *Lupinus* plants within their corn fields, because those plants act as trap crops for *Macro-dactylus* sp. (Altieri 1993a).

**Plant Disease Management in Traditional Agriculture**

Thurston (1992) reviewed most of the literature available on the cultural practices used by thousands of small traditional farmers in developing countries, and he concluded that although some are highly labor-intensive, they are sustainable and deserve more respect than they receive. He considered a number of traditional agricultural systems and compared them for their productivity (crop yield or income produced), sustainability (ability to maintain the system in existence over a very long period of time even when subjected to stress), stability (obtaining consistent and reliable yields in both the short and long run), and equitability (relative distribution of wealth in a society) (Table 6.3). The main recommendations derived from Thurston's survey include:

1. Many sustainable agricultural systems incorporate large quantities of organic matter into soil, soilborne disease, in addition to other important agronomic benefits.
2. Some diseases are suppressed by shade, whereas others increase in importance under shade. Manipulation of shade should be considered as a possible component of disease management systems.
3. The use of antagonistic plants (trap crops/trap plants) is useful for the management of nematodes and other soilborne pathogens.
4. Clean seed or healthy propagating material, or such material treated to kill pathogens, often has positive and dramatic effects on plant health and crop yields.
5. Plant pathogens are often transmitted when vegetative propagating material is cut. Using sterile tools for cutting propagating material and the use of uncut propagation materials are important practices. For example, planting whole rather than cut potato tubers prevents losses due to fungi and bacteria that occur when tubers are cut.
6. The density of crop or plant stands has important effects on disease incidence and severity. Dense plant stands generally increase disease, but in some cases (i.e., with some virus diseases) may reduce disease. Crop density can be altered by manipulating the rate of plant and row spacing.
7. The depth at which seeds and propagating materials are planted may affect disease incidence or severity and should be looked into when
designing disease management strategies. Shallow planting is often an effective disease management practice, as plants emerge from the soil quickly when not planted too deeply.

8. Fallow periods are beneficial in reducing losses from plant diseases, especially soilborne diseases. Fallowing is generally more effective in combination with rotations.

9. Fire and heat are often overlooked as plant disease management practices. The high temperatures produced by burning can eliminate the inoculum of many pathogens.

10. Traditional agriculture has utilized flooding extensively for the management of plant pathogens. For example, the paddy rice system, in addition to its various agronomic benefits, has an important role in reducing the importance of soilborne diseases.

11. Mulches reduce plant diseases by reducing soil splashing, influencing the moisture content and temperature of the soil, and enhancing the microbiological activities that suppress plant pathogens.

12. It is difficult to generalize with any degree of accuracy about disease management through the use of multiple cropping. Recommendations on multiple cropping should be thoroughly tested, and site-specific recommendations will often be necessary.

13. Multistory systems existed for centuries in tropical areas without major disease problems. Combining manipulations of plant architecture and shade, the use of land races, and a diversity of species, multistory systems may provide useful models for other areas in the tropics.

14. Raised fields, raised beds, ridges, and mounds were used widely by traditional farmers for millennia. Better drainage and irrigation, enhanced fertility, and frost control are other important benefits of these systems, but planting in soil raised above the soil surface is also an important disease management practice for soilborne pathogens.

15. The use of rotation should be carefully investigated and utilized in schemes designed to aid traditional farmers, keeping in mind that the value of crop rotation for the management of specific diseases is highly location specific.

In-Situ Conservation and Management of Crop Genetic Resources

Traditional agroecosystems are genetically diverse, containing populations of variable and adapted land races as well as wild relatives of crops (Harlan 1976). Land race populations consist of mixtures of genetic lines, all of which are reasonably adapted to the region in which they evolved, but which differ in reaction to diseases and insect pests. Some lines are resistant or tolerant to certain races of pathogens and some to other races (Harlan 1976). The resulting genetic diversity confers at least partial resistance to diseases that
**TABLE 6.3 Sustainability, external inputs needed, and labor requirements of selected plant disease management practices of traditional farmers (Thurston 1992).**

<table>
<thead>
<tr>
<th>Practice</th>
<th>Sustainable</th>
<th>External Inputs</th>
<th>Labor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusting crop density</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Adjusting depth of planting</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Adjusting time of planting</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Altering of land and crop architecture</td>
<td>Yes</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Biological control (soilborne pathogens)</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Burning</td>
<td>Yes*</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Fallowing</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Flooding</td>
<td>Yes</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Manipulating shade</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Mulching</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Multistory cropping</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Multiple cropping</td>
<td>Yes</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Planting diverse crops</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Planting in raised beds</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Rotation</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Site selection</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Tillage</td>
<td>No</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Using organic amendments</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Weed control</td>
<td>No</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

* Under high population pressure the slash and burn system is neither stable nor sustainable.

are specific to particular strains of the crop and allows farmers to exploit different microclimates and derive multiple uses from the genetic variation of a given species.

Andean farmers cultivate as many as 50 potato varieties in their fields and have a four-tiered taxonomic system for classifying potatoes (Brush et al. 1981). Similarly, in Thailand and Indonesia, farmers maintain a diversity of rice varieties that are adapted to a wide range of environmental conditions. Evidence suggests that folk taxonomies become more relevant as areas become more marginal and risky. In Peru, for example, as altitude increases, the percentage of native stock increases steadily. In Southeast Asia, farmers
plant modern semi-dwarf rice varieties during the dry season and sow traditional varieties during the monsoon season, thus taking advantage of the productivity of irrigated modern varieties during dry months, and of the stability of native varieties in the wet season when pest outbreaks commonly occur (Grigg 1974). Clawson (1985) described a number of systems in which traditional tropical farmers plant multiple varieties of each crop, providing both intraspecific and interspecific diversity, thus enhancing harvest security.

A number of plants within or around traditional cropping systems are wild relatives of crop plants. Thus, through the practice of nonclean cultivation, farmers have inadvertently increased the gene flow between crops and their relatives (Altieri and Merrick 1987). For example, in Mexico, farmers allow teosinte to remain within or near cornfields so that natural crosses occur when the wind pollinates corn (Wilkes 1977). Through this continual association, fairly stable equilibria have developed among crops, weeds, diseases, cultural practices, and human habits (Bartlett 1980). The equilibria are complex, and difficult to modify without upsetting the balance, thus risking loss of genetic resources. For this reason Altieri and Merrick (1987) have supported the concept of in-situ conservation of many land races and wild relatives. They argue that in-situ conservation of native crop diversity is achievable only through preservation of agroecosystems under traditional management, and furthermore, only if this management is guided by the local knowledge of the plants and their requirements (Alcorn 1984).

Many peasants preserve and use naturalized ecosystems (forests, hillsides, lakes, grasslands, streamways, swamps) within or adjacent to their properties. These areas provide valuable food supplements, construction materials, medicines, organic fertilizers, fuels, and religious items (Toledo 1980). Although gathering has normally been associated with poverty (Wilken 1969), recent evidence suggests that this activity is closely associated with a strong cultural tradition. In addition, vegetation gathering has an economic and ecological basis, as wild plants provide significant input to the subsistence economy, especially when agricultural production is low due to natural calamities or other circumstances (Altieri et al. 1987). In fact, in many areas of semi-arid Africa, peasant and tribal groups maintain their nutritional level through gathering even when drought strikes (Grivetti 1979). Gathering is also prominent among shifting cultivators whose fields are widely spaced throughout the forest. Many farmers collect wild plants for the family cooking pot while traveling between fields (Lenz 1986). Gathering is also prevalent in desert biomes. For example, the Pima and Papago Indians of the Sonora Desert supply most of their subsistence needs from more than 15 species of wild and cultivated legumes (Nabhan 1983). In humid, tropical conditions the procurement of resources from the primary and secondary forest is even more impressive. For example, in the
Uxpanapa region of Veracruz, Mexico, local peasants exploit about 435 wild plant and animal species, of which 229 are used as food (Toledo et al. 1985).

Examples of Traditional Farming Systems

Paddy Rice Culture in Southeast Asia

Beneath the simple structure of the rice paddy monoculture (sawah) lies a complex system of built-in natural controls and genetic crop diversity (King 1927). Although these systems are more prevalent in Southeast Asia, upland rice farmers in the Latin American tropics also grow a number of photoperiod-sensitive rice varieties adapted to differing environmental conditions. These farmers regularly exchange seed with their neighbors because they observe that any one variety begins to suffer from pest problems if grown continuously on the same land for several years. The temporal, spatial, and genetic diversity resulting from farm-to-farm variations in cropping systems confers at least partial resistance to pest attack. Depending on the degree of diversity, food web interactions among the insect pests of rice and their numerous natural enemies in paddy fields can become very complex, often resulting in low but stable insect populations (Matteson et al. 1984).

The rice ecosystem, where it has existed over a long period, also includes diverse animal species. Some farmers allow flocks of domestic ducks to forage for insects and weeds in the paddies. Many farmers allow aquatic weeds, which they harvest for food (Datta and Banerjee 1978). Frequently one finds paddies where farmers have introduced a few pairs of prolific fish (such as common carp, *Sarotherdon mossambicus*). When the water is drained off to harvest the rice, the fish move to troughs or tanks dug in the corners of fields and are then harvested.

The techniques used for rice/fish culture differ considerably from country to country and from region to region. In general, exploitation of rice field fisheries may be classified as captural or cultural (Pullin and Shehadeh 1980). In the captural system, wild fish populate and reproduce in the flooded rice fields and are harvested at the end of the rice-growing season. Captural systems occupy a far greater area than cultural systems and are important in all the rice-growing areas of Southeast Asia. In the cultural system the rice field is stocked with fish. This system may be further differentiated into a concurrent culture, in which fish are reared concurrently with the rice crop, and a rotation culture, in which fish and rice are grown alternately. Fish can also be cultured as an intermediate crop between two rice crops (Ardiwinita 1957).

Traditional paddy rice growers usually produce only one rice crop each year during the wet season, even when irrigation water is readily available.
This practice is partly an attempt to avoid damage by rice stem borers. For the remainder of the year the land may lie fallow and be grazed by domestic animals. This annual fallow, along with the dung dropped by the grazing animals and the weeds and stubble plowed into the soil, will usually sustain acceptable rice yields (Webster and Wilson 1980).

Alternatively, farmers may follow rice with other annual crops in the same year where adequate rainfall or irrigation water is available. Planting alternative rows of cereals and legumes is common, as farmers believe it uses the soil resources more efficiently. Well-rotted composts and manures are applied to the land to provide nutrients for the growing crops. Sowing cowpeas or mung beans into standing rice stubble reduces damage by bean flies, thrips, and leafhoppers, by interfering with their ability to find their host (Matteson et al. 1984).

The micro-environment of the sawah also helps the wet-rice cultivator to produce constant crop yields from the same field year after year. First, the water-covered sawah is protected from high temperatures and the direct impact of rain and high winds, thus reducing soil erosion. Second, the high water table reduces the vertical movement of water, thus limiting nutrient leaching. Third, both floods and irrigation water bring silt in suspension and other plant nutrients in solution, renewing soil fertility each year. Fourth, the water in the sawahs contains Azolla spp. (a symbiotic association of blue-green alga and fern), which promotes the fixation of nitrogen—adding up to 50 kg per hectare of nitrogen.

Javanese Traditional Agriculture

In Java, Indonesia, many traditional agricultural systems combine crops and/or animals with tree crops or forest plants. Some of these are agroforestry systems and can be grouped into two major types (Marten 1986):

_Talun-kebun_. This is an indigenous Sundanese agricultural system that appears to have derived from shifting cultivation. It usually consists of three stages—kebun, kebun-campuran and talun—each of which serves a different function. In the kebun, the first stage, a mixture of annual crops is usually planted. This stage is economically valuable since most of the crops are sold for cash. After two years, tree seedlings have begun to grow in the field and there is less space for annual crops. At this point the kebun gradually evolves into a kebun-campuran, where annuals are mixed with half-grown perennials. This stage has economic value but also promotes soil and water conservation. After the annuals are harvested, the field is usually abandoned for two to three years to become dominated by perennials. This third stage is known as talun and has both economic and biophysical values.

After the forest is cleared, the land can be planted to huma (dryland rice) or sawah (wet rice paddy), depending on whether irrigation water is
available. Alternatively, the land can be turned directly into kebun by planting a mixture of annual crops. In some areas kebun is developed after harvesting the huma by following the dryland rice with annual field crops. If the kebun is planted with tree crops or bamboo, it becomes kebun-campuran (mixed garden), which after several years will be dominated by perennials and become talun (perennial crop garden). It is not uncommon to find talun-kebun composed of up to 112 species of plants. Of these plants about 42 percent provide for building materials and fuelwood, 18 percent are fruit trees, 14 percent are vegetables, and the remainder constitute ornamentals, medicinal plants, spices, and cash crops.

**Pekarangan (Home Garden).** The pekarangan is an integrated system of people, plants, and animals with definite boundaries and a mixture of annual crops, perennial crops, and animals surrounding a house. A talun-kebun is converted into a perkarangan when a house is built upon it. Instead of clearing the trees to cultivate field crops as in talun-kebun, the home garden trees are kept as a permanent source of shade for the house and the area around it, and field crops in the home garden are planted beneath the trees.

A typical home garden has a vertical structure from year to year, though there may be some seasonal variation. The number of species and individuals is highest in the lowest story and decreases with height. The lowest story (less than one meter in height) is dominated by food plants like spices, vegetables, sweet potatoes, taro, **Xanthosoma**, chili pepper, eggplant, and legumes. The next layer (one to two meters in height) is also dominated by food plants, such as ganyong (**Canna edulis**), **Xanthosoma**, cassava, and **gembili** (**Dioscorea esculenta**). The next story (two to five meters) is dominated by bananas, papayas, and other fruit trees. The five to ten meter layer is also dominated by fruit trees, for example soursop, jack fruit, pisitan (**Lansium domesticum**), guava, mountain apple, or other cash crops, such as cloves. The top layer (10 meters) is dominated by coconut trees and trees for wood production, like **Albizzia** and **Parkia**. The overall effect is a vertical structure similar to a natural forest, a structure that optimizes the use of space and sunlight. The most common plants in the pekarangan are cassava (**Manihot esculenta**) and ganyong (**Canna edulis**). Both have a high calorie content and are important as rice substitutes.

There are definite groupings of plants in the home garden. For example, wherever gadung is found, petai (**Parkia speciosa**), kemlakian, and rambutan, possibly guava (**Psidium guajava**), and suweg (**Amorphophalus campanulatus**) will probably also be present.

An important plant association consists of rambutan (**Nephelium lappaceum**), kelor (**Moringa pterygosperma**), rose (**Rosa hybridia**), mangkokan (**Polyscias scutellaria**), gadung (**Dioscorea hispida**), and grapefruit (**Citrus grandis**). Each of the plants in this association provides the farmer with
something useful. Rambutan fruit is sold and eaten; kelor is used as a vegetable and is also believed to be a magical plant; rose is grown for pleasure; mangkokan is grown as an aesthetic plant and is used occasionally for hedges and hair tonic; gadung is a food plant that can also be used as a weather indicator because the rainy season usually begins a short time after its leaves start to grow; grapefruit has a similar function, and when its fruits start to grow the season of annual plant cultivation begins. These weather and planting-time indicators are important; many farmers believe agricultural failures are due mainly to improper planting times.

Livestock form an important component of this agroforestry system, particularly poultry, but also sheep freely grazing or fenced in sheds and fed with forage gathered from the vegetation. The animals have an important role in nutrient recycling. Also fish ponds are common and the fish are fed with animal and human wastes.

Mixed Tree Systems in Mexico

Mixed tree systems or home gardens are also common in the tropical lowlands of Mexico where they constitute a common but understudied form of agriculture. These systems involve the planting, transplanting, sparing, or protecting of a variety of useful species (from tall canopy trees to ground cover and climbing vines) for the harvest of various forest products, including firewood, food for the household and marketplace, medicines, and construction materials (Gliessman 1990).

Home gardens in Mexico are plots of land that include a house surrounded by or adjacent to an area for raising a variety of plant species and sometimes livestock. They are also known as kitchen gardens, dooryard gardens, huertos familiares, or solares. The home garden is representative of a household's needs and interests, providing food, fodder, firewood, market products, construction material, medicines, and ornamental plants for the household and local community. Many of the more common trees are those same species found in the surrounding natural forests, but new species have been incorporated, including papaya (Carica papaya), guava (Psidium spp.), banana (Musa spp.), lemon (Citrus limon), and orange (Citrus aurantium). In light gaps or under the shade of trees, a series of both indigenous and exotic species of herbs, shrubs, vines, and epiphytes is grown. Seedlings from useful wild species brought into the garden by the wind or animals are often not weeded out and are subsequently integrated into the home garden system.

One of the most striking features of present-day Mayan towns in the Yucatan Peninsula is the floral richness of the home gardens. In a survey of the home gardens in the town of Xululub, 404 species were found where only 1,120 species are known for the whole state. Home gardens also provide
diverse environments where many wild species of animals and plants can live, although the diversity of species depends on the size of the gardens and the degree of management. Estimated average family plots range from 600 m² to 6,000 m². Taking into consideration that most households in rural communities of the Yucatan Peninsula have some type of home garden, local traditional practices of orchard management have already contributed to the forest cover in the peninsula and have the potential for contributing more (Gliessman 1990).

**Shifting Cultivation**

Shifting cultivation is also called slash-and-burn or *swidden* agriculture and is usually defined as an agricultural system in which temporary clearings are planted for a few years with annual or short-term perennial crops, and then allowed to remain fallow for a period longer than they were cropped. Conditions that limit crop yields, such as soil fertility losses, weeds, or pest outbreaks, are overcome during the fallow time, and after a certain number of years the area is ready to be cleared again for cropping. Thus, these systems involve a few years of cultivation alternating with several years of fallow to regenerate soil fertility. Typically there are three types of fallow: forest fallow (20 to 25 years), bush fallow (six to 10 years) and grass fallow (less than five years).

Within the tropics, shifting cultivation is most important in Africa. In Asia and tropical America it is practiced by disadvantaged people in remote rural areas where the lack of roads precludes the development of markets for cash crops. In South and Southeast Asia, about 50 million people are shifting cultivators, cropping 10 to 18 million hectares each year. With the gradual development of rice cultivation in lowland areas, shifting cultivation has retreated to hilly areas unsuitable for paddy. In tropical America, shifting cultivation was practiced before 1,000 B.C. It is based on corn, beans, and squash in the drier tropical areas of Mexico, and on tubers, cassava, and sweet potatoes in the wetter lowlands (Norman 1979). The features of shifting cultivation include (Grigg 1974):

- The size and number of plots managed by each family varies with the soil fertility, population density, length of the fallow, and degree of commercialization.
- It may or may not require a shift of domicile.
- Land tenure is usually communal, and most farmers have cooperative arrangements to work the land, particularly to clear the vegetation.
- Methods of cultivation are based on human and animal power, characterized by hand tools.
- Farm livestock play a minor role.
• Little cultivation and management are done once the crops are sown.
• Generally, soil fertility is maintained with some animal manure, but mostly with the nutrients provided by the ash and decomposing vegetation. In warm wet conditions, relatively rapid decomposition of the mulch provides nutrient recycling benefits unavailable through burning, while protecting the soil surface and increasing the amount of organic matter in the soil (Thurston 1991).

It is common in shifting cultivation to cut a parcel of forest and burn the area to release nutrients and eliminate weeds. A mixture of short-term crops, sometimes followed by perennials, is grown until the soil loses its fertility and competition from successional plant species is severe. Then the farmer prepares a new field and the old one returns to long-term fallow. During the fallow period, large quantities of nutrients are stored in the plant biomass. These nutrients are released when the fallow vegetation is burned to clear the land for the next cropping cycle (Rutenberg 1971). Where land is abundant and resources scarce, it is generally agreed this is an efficient and stable system that has sustained farm families for many generations. Due to recent population pressure, to the pressure of poverty, and factors like weed growth and declining soil fertility, the fallow cycle has been reduced from a more favorable 20 to 30 years to a period as short as five years, leading in many cases to soil losses and nutrient depletion. Unless there are substantial social and economic changes, including land redistribution, short-term cycles will continue and more land will be cleared.

Although there is generally a random generation of species during the fallow periods, in certain parts of the humid tropics farmers intentionally retain certain species such as *Acioa baterii*, *Anthonata macrophylla*, and *Alchornea* sp. The small trees are only trimmed and the big branches are left for staking crops. The cut tops are spread on the soils and burned. Thus, the bush fallow functions doubly to provide staking materials and recycle nutrients (Nye and Greenland 1961). The distinction between an agricultural plot and the adjacent mature forest in the humid tropics may not be as clearly evident as in temperate regions. Rather than being separate categories of vegetation, *milpas* (small cleared fields) and mature forest patches are different stages of the cyclical process of shifting agriculture. Even mature vegetation is part of a more extensive management system that includes sparing trees in the milpa and protecting and cultivating useful plant species during the regrowth of the forest patch. These forest patches, along with other uncut areas where the mature vegetation is protected or where useful tree species have been encouraged or transplanted, can be considered forest gardens, managed forests, or modified forests.

It has been speculated that bush fallows are potentially valuable in controlling insects. The great diversity of crops grown simultaneously in
shifting cultivation helps prevent pest buildup on the comparatively isolated plants of each species. Increased parasitoid and predator populations, decreased colonization and reproduction of pests, chemical repellency or masking, feeding inhibition from non-host plants, prevention of pest movement or stimulation of pest emigration and optimal synchrony between pests and their natural enemies are presumably important temporal and spatial factors in regulating pests in polycultures. Shade from forest fragments still standing in new fields, coupled with a partial canopy of fruit, nut, firewood, medicinal and/or lumber tree species reduces shade-intolerant weed populations and provides alternative hosts for beneficial (or sometimes detrimental) insects. Clearing comparatively small plots in a matrix of secondary forest vegetation permits easy migration of natural control agents from the surrounding jungle (Matteson et al. 1984).

**The Nkomanjila System of the Nyhia Shifting Cultivators**

This is a typical shifting cultivation system and involves a cycle of cutting woodland, burning, cropping, and fallow (King 1978). The Nyhia cultivators prefer fully regrown or virgin woodland composed of specific trees, such as *Brachystegia* spp. and *Acacia macrothyrsa*. In burning the nkomanjila, cut wood is stacked around tree trunks and burned just before the rainy season. If much unburned material remains, it is gathered and reburned. After one month, during which other fields are prepared, the crops are planted. Before planting, ash from the burned trees is spread with hoes evenly through the field, and weeds are hoed into the soil. Seeds are broadcast and lightly hoed.

The nkomanjila must be weeded, usually once but sometimes twice. Women do the weeding and harvesting, while men do the cutting, burning, and some of the initial hoeing. After harvesting, the crop is dried in the sun and then stored.

Nkomanjila crops include finger millet, perennial sorghum, pulses (including pigeon peas, lima beans, and cowpeas), and cucurbits (including pumpkins and gourds) in intercropping patterns.

The standard crop sequence in nkomanjila is the finger millet/sorghum complex the first year, followed by sorghum ratoons or suckers the second year. A portion of the first-year field may be planted to an early maturing variety of finger millet. The second year of sorghum ratoons (*lisala*) is virtually untended except for harvesting. Traditionally, the cropping sequence ended here and the field was abandoned to fallow. Today, however, so much acreage is needed for food production that these long crop sequences are no longer possible. The basic two-year nkomanjila sequences may be repeated. Alternatively, if the finger millet yield the first year is good,
the basic pattern may be reinitiated in the second year. Once the nkomanjila is abandoned (which may be due to weed growth or lower soil fertility), the land is allowed to rest about five to seven years. Given current population densities in Africa, the nkomanjila system is no longer viable since farmers can no longer afford long fallow periods. As a result of frequent cultivation and burning, a cultivation system involving a grass-dominated fallow has replaced the woodland-dominated fallow.

The Nkule System. The nkule system is the grassland alternative to nkomanjila (King 1978). Techniques used in nkule cultivation can be applied both to upland grass communities, resulting in fields known as nkule, and at higher elevations, where the fields are called ihombe. Indicators for the nkule method include tall grasses of the Hyparrhenia genus and Trachypogon spicatus. The distinctive feature of the nkule system is that turf and soil are mounded over grass, which is then burned under the mound. Maize and cucurbits are planted under the mound. In December the mounds around these crops are hoed down. Ash and burned soil are then spread and finger millet is sowed. The field requires two weedicings, one in the course of hoeing down the mounds and preparing the seedbed, and a second during the growing season. The finger millet crop is harvested and stored as under the nkomanjila system. In ihombe fields, mounds are made and burned, but finger millet is the only crop planted after the mounds have been spread.

Burning both vegetative matter and surface soil is important in the nkule system. Usually, fallow grassland is plowed during the dry season to break the sod, which is then hoed into mounds. Cow dung is put on the windward side of the mound and set afire. The soil and turf of the mound is slowly hoed over the burning dung until all vegetative matter has been burned.

The important difference between nkule and ihombe fields is that in the nkule crops are virtually always growing, while the ihombe is used for just one year and fallowed at least three years. In upland nkule fields, the crop sequences are as varied as after nkomanjila. An upland nkule field is ideally put into a legume/grain rotation for two to four years, then rested one or two years. Now, many fields of nkule origin are cultivated for six or more years. As in nkomanjila, cassava often ends the cropping sequence, although the wheat/early beans rotation appears to be viable over a long period.

Occasionally an ihombe field will be planted to finger millet a second year or, if well up on the margin, hoed into large ridges for beans and groundnuts. Failure of a second crop of finger millet (or most other crops) may be due to a lack of particular micronutrients in ihombe fields or to alterations of the soil structure. When the soils are continuously cultivated, iron can accumulate in the soil, impeding drainage in subsequent years. A short fallow may reverse this condition.
Slash/Mulch Systems and the "Frijol Tapado" System in Central America

Frijol tapado is a traditional agricultural system used to produce beans in mid-elevation areas of Central America on steep slopes with high amounts of rainfall where most beans in the region are grown. Originally devised by the indigenous inhabitants of Central America, it is one of the few agricultural technologies transferred to the Spanish colonizers. To begin the process, farmers choose a fallow field that is two to three years old so that the woody vegetation dominates the grasses. If the fallow period is less than two years, then the grasses will be able to out-compete the emerging bean plants and soil fertility will not have been fully restored since last harvest. Next, paths are cut through the field with machetes. Then bean seeds are thrown into the fallow vegetation, or broadcasted. Finally, the fallow vegetation with bean seed is cut down into a mulch that is allowed to decay and provide nutrients to the maturing bean seedling. Approximately twelve weeks after broadcasting a harvest is made. In Costa Rica, the estimate is that sixty to seventy percent of the beans in the country are produced by frijol tapado. Compared to the other more labor- and chemical-intensive methods of bean production used by the small holder, the tapado system has a higher rate of return because of lower costs.

The tapado system allows production of beans for both home consumption and cash to supplement meager incomes during times of financial hardship. The cost-effective benefits include: (1) no need for expensive and potentially toxic agricultural chemicals such as fertilizers and pesticides and (2) a relatively low labor requirement. Soil erosion is minimized because of a continuous vegetation cover that prevents exposing the bare ground to heavy rainfall.

The alternative to the tapado system is the espequeado system where the farmer plants the beans into the bare soil with a stick. In comparison to the tapado system, espequeado has higher costs of production and therefore a lower rate of return. The system requires agricultural chemicals and more labor, which creates the higher expense. Small farmers do not have access to the cash and credit required to buy the needed agricultural chemicals. Technical assistance is also not readily available. Incomplete implementation of the guidelines for the espequeado system as established by the government agricultural agencies results in soil degradation and a decline in productivity. A loss of money is the economic consequence for the small farmer's partial use of the espequeado system. The government agricultural agencies are promoting it over the tapado system because it is supposed to have higher yields per hectare, but this has not been established by the literature. In addition, pests seem to be a greater problem in the espequeado system.
Scientists studying and promoting slash/mulch systems similar to the frijol tapado in Central America report several advantages for the farmers (Thurston et al. 1984):

1. The slash/mulch systems can add large quantities of organic matter to the soil. Velvet beans (Stizilobium spp. and Mucuna pruriens) commonly produce up to 50 T/ha organic matter each year. These mulches can also fix large amounts of nitrogen in the soil. For example, velvet beans can fix up to 150 kg N/ha and Lathyrus nigrivalvis almost as much. The combination of nitrogen and organic matter has meant that farmers using several of the mulch systems, without added chemical fertilizers, can harvest up to 3 T/ha corn per year.

2. Mulches can reduce the amount of work spent in weeding. In some cases they can eliminate the second weeding and in others eliminate the weeding in the second corn crop. Farmers in several parts of Central America, Africa, and Asia use velvet beans to eliminate the worst of the weeds such as Cyperus rotundus and Imperata cylindrica.

3. Another advantage is conferred by the alternative uses for these crops. Velvet beans, lablab, and L. nigrivalvis provide good forage. The last two can withstand drought and thus provide high-quality forage during the dry season. The velvet bean, jack bean, runner bean, and lablab are all nutritious, high protein foods for human consumption, which can be prepared in various ways. Velvet beans are used to make coffee, chocolate, bread, and tortillas. Lablabs can be eaten fresh like peas or dried like other dried pulses. In many cases, the consumption of these beans, which are a free by-product of the operation, has resulted in a surprising improvement in the nutrition of children.

4. Other advantages may arise depending on the mulch species used. Velvet beans can be used as a wide spectrum nematicide and jack bean leaves are sometimes used to eliminate leaf cutter ant colonies.

**Agropastoral Systems**

Farming systems that combine animal and crop production vary across agroecological zones (McDowell and Hildebrand 1980). In Asian lowland rice farming areas, buffalos are important animal components and provide (1) traction for cultivating fields and (2) milk and meat that are consumed domestically or sold in markets. Cattle, fowl (mainly chickens and ducks), and swine are also commonly raised on these farms. Feeds include crop residues, weeds, peelings, tops of root crops, bagasse, hulls, and other agricultural by-products. In highland areas, swine, poultry, buffalo, and cattle are raised in combination with rice, maize, cassava, beans, and small grains. The cropping systems of tropical humid Africa are dominated by rice, yams, and plantains (McDowell and Hildebrand 1980, Ruthenberg
Goats and poultry are the dominant animals. Sheep and swine are less abundant, but still common. Feeds include fallow land forage, crop residues, cull tubers, and vines. The small farms of Latin America typically include crop mixtures of beans, maize, and rice (McDowell and Hildebrand 1980, Ruthenberg 1971). Cattle are common and maintained for milk, meat, and draft. Swine and poultry are raised for food or for sale. Pastures, crop residues, and cut feeds support animal production.

Several other benefits accrue from agropastoral systems. In effect, incorporation of livestock into farming systems adds another trophic level to the system. Animals can be fed plant residues, weeds, and fallows with little impact on crop productivity. This serves to turn otherwise unusable biomass into animal protein, especially in the case of ruminants. Animals recycle the nutrient content of plants, transforming them into manure and allowing a broader range of fertilization alternatives in managing farm nutrients. The need for animal feed also broadens the crop base to include species useful for conserving soil and water. Legumes are often planted to provide quality forage and serve to improve nitrogen content in soils.

Beyond their agroecological interactions with crops, animals serve other important roles in the farm economy. They produce income from meat, milk, and fiber. Livestock increase in value over time and can be sold for cash in times of need or purchased when cash is available (McDowell and Hildebrand 1980).

**Integrated Agriculture-Aquaculture**

In many parts of Asia, the productive use of land and water resources has been integrated into traditional farming systems. Farmers have transformed wetlands into ponds separated by cultivable ridges. An example is the dike-pond system which has existed for centuries in South China. To produce or maintain the ponds, soil is dug out and used to repair the dikes around it. Before being filled with river water and rainwater, the pond is prepared for fish rearing by clearing, sanitizing, and fertilizing with local inputs of quicklime, tea-seed cake, and organic manure. The fish stocked in the pond include various types of carp, which are harvested for home consumption and sale. Mulberry is planted on the dikes, fertilized with pond mud and irrigated by hand with nutrient-rich pond water. Mulberry leaves are fed to silkworms; the branches are used as stakes to support climbing vegetables and as fuelwood. In sheds, silkworms are reared for yarn production. Their excrements, mixed with the remains of mulberry leaves are used as fish feed. Sugarcane plants on the dikes provide sugar. Young leaves are used to feed fish and pigs, and old leaves to shade crops, for roofing thatch, and for fuel; the roots are also used as fuel. Grass and vegetables are also grown on the dikes to provide food for the fish and
family. Pigs are raised mainly to provide manure but also for meat. They are fed sugarcane tops, by-products from sugar refining, aquatic plants, and other vegetable wastes. Their feces and urine, as well as human excrement and household wastes, form the principle organic inputs into the fish pond (Ruddle and Zhong 1988).

Overall integrated farming systems that include semi-intensive aquaculture are less risky for the resource-poor farmer than intensive fish farms, because of their efficiency derived from synergisms among enterprises, their diversity of produce, and their environmental soundness. In many traditional systems aquaculture goes beyond fish production and cash income as pond water and pond biota perform many ecological, social, and cultural services on an integrated farm. Thus aquaculture and water management act as an engine driving the sustainability of the entire farming system (Lightfoot 1990).

**Andean Agriculture**

Between 3,000 and 4,000 years ago, a nomadic, hunting and gathering way of life in the Central Andes was supplanted by a village-based agropastoral economy, a system that still prevails despite competition for land between haciendas and peasant communities (Brush 1982). The impact of the complex Andean environment on the human economy has resulted in vertical arrangements of settlements and agricultural systems (Table 6.4). The pattern of verticality derives from climatic and biotic differences related to altitude and geographical location. The most important cultural adaptation to these environmental constraints has been the subsistence system: crops, animals, and agropastoral technologies designed to yield an adequate diet with local resources while avoiding soil erosion (Gade 1975).

The evolution of agrarian technology in the Central Andes has produced extensive knowledge about using the Andean environment. This knowledge affected the division of the Andean environment into altitudinally arranged agroclimatic belts, each characterized by specific field and crop rotation practices, terraces and irrigation systems, and the selection of many animals, crops, and crop varieties (Brush et al. 1981). About 34 different crops (corn, quinoa, *Amaranthus caudatus*), legumes (beans, lupine, lima beans), tubers (species of potato, manioc, *Arrachocha*, etc.), fruits, condiments, and vegetables are grown. The main crops are corn, chenopods (*Chenopodium quinoa* and *C. pallidicaule*), and potatoes. Individual farmers may cultivate as many as 50 varieties of potatoes in their fields, and up to 100 locally named varieties may be found in a single village. The maintenance of this wide genetic base is adaptive since it reduces the threat of crop loss due to pests and pathogens specific to particular strains of the crop (Brush 1982).
Crop Patterns in the Agroclimatic Belts. The local inhabitants recognize three to seven agroclimatic belts, distinguished according to altitude, moisture, temperature, vegetation, land tenure, crop assemblages, and agricultural technology (Table 6.4). There is considerable regional variation in the cultivation patterns of each belt. For example, in the communities of Amaru and Paru-Paru in Cuzco, Peru, three main belts can be distinguished (Gade 1975). Sites in the corn belt have soft slopes, located between 3,400 and 3,600 meters. These sites are irrigated and farmed in three alternative four-year rotations: (1) corn/fava beans/corn/fallow; (2) corn/corn/potato or fallow; and (3) potato and barley/fava beans/corn/corn. The potato/fava/cereals belt is composed of sites with steep slopes, located from 3,600 to 3,800 meters. Potatoes are intercropped with barley, wheat, fava beans and peas. In rainfed areas there are two main four-year rotations: (1) fava beans/wheat/peas/barley and (2) Lupinus mutabilis/barley/fava beans/fallow. In irrigated areas common rotations are: (1) potato/wheat/fava beans/barley and (2) potato or C. quinoa/barley/peas/fallow. The bitter potato/pasture belt is a cold belt located above 3,800 meters. Rainfed rotations in this belt usually

TABLE 6.4 Agroclimatic crop zones of the central Andes (based on Brush 1982).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Major Crops/Animals</th>
<th>Agricultural Technology</th>
<th>Land Tenure</th>
<th>Focus of Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasture above 3,800.</td>
<td>alpacas</td>
<td>communal</td>
<td>communal ownership &amp;</td>
<td>market (esp. wool) and</td>
</tr>
<tr>
<td></td>
<td>llamas</td>
<td></td>
<td>communal use</td>
<td>subsistence</td>
</tr>
<tr>
<td></td>
<td>sheep</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cattle</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Tuber 3,000-4,200m.</td>
<td>potatoes</td>
<td>hoe</td>
<td>communal</td>
<td>subsistence</td>
</tr>
<tr>
<td></td>
<td>quinoa/canihua</td>
<td>foot plow</td>
<td>ownership</td>
<td></td>
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<tr>
<td></td>
<td>barley</td>
<td>dung as</td>
<td>with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>other native tubers</td>
<td>fertilizer</td>
<td>individual use</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(mashua, ulluca, oca)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cereal 1,500-3,000m.</td>
<td>corn</td>
<td>draft animals</td>
<td>private ownership</td>
<td>subsistence (grains) and</td>
</tr>
<tr>
<td></td>
<td>wheat</td>
<td>some</td>
<td>and use</td>
<td>market (fruits and vegetables)</td>
</tr>
<tr>
<td></td>
<td>cucurbits</td>
<td>mechanization</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>beans</td>
<td>chemical</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>temperate fruits</td>
<td>fertilizer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>and vegetables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropical/fruit 500-1,500m.</td>
<td>cocoa</td>
<td>mainly agro-</td>
<td>private ownership</td>
<td>market</td>
</tr>
<tr>
<td></td>
<td>sugarcane</td>
<td>industrial</td>
<td>and use</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cotton</td>
<td>technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>tropical fruit</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>corn</td>
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</tbody>
</table>
include a four- to five-year fallow period, after a four-year sequence of potato/Oxalis tuberosa and Ullucus tuberosus/U. tuberosus and Tropaeolum tuberosum/barley.

**Traditional Farming Systems of Mediterranean Chile**

The small farmers (campesinos) of mediterranean Chile emphasize diversity to use scarce resources most efficiently. Farming systems are usually either small-scale and intensive or more extensive and semi-commercial.

**Small-Scale Intensive Systems**

These systems rarely exceed one hectare in size and therefore usually do not provide all the food requirements of the family. All items produced are used on the farm, and other needs are bought with earnings from off-farm work. Campesinos typically produce a great variety of crops and animals, and it is not unusual to find as many as five to 10 tree crops, 10 to 15 annual crops, and three to four animal species on a single farm.

These farms often include an arbor of grapes (parron) to provide shade, along with fruit, herbs, medicinal plants, and flowers in addition to the tree and annual food crops. The typical animals on these farms are rabbits, free-ranging chickens and ducks, and occasionally a few pigs feeding on kitchen waste and crop residue. Intensive annual cropping usually makes use of simple crop patterns (growing annual crops only during the spring and summer), or, more typically, crop sequencing (planting a second crop after the harvest of the first). In both crop patterns, campesinos may practice intercropping. Common intercropping systems include corn/beans, garlic and/or onion mixed with lettuce and cabbage, and corn/potatoes.

Figure 6.4 depicts one very complex system in the central coast range. The land, characterized by a 25 percent slope, was divided into two sections. Half of it is devoted to annual crops and herbs grown in rows running parallel to the hill contour. The fruit trees include several varieties of grapes, a few non-crop trees such as pine (Pinus radiata), aromo (Acacia spp.), Datura spp. and a small stand of bamboo and cactus (Opuntia spp.). A living fence of cypress separates the two sections. Chickens and rabbits are raised under the orchard in cages, and their manure, mixed with sawdust, is used to fertilize crops and trees. In addition to the fruit trees, Eucalyptus spp. are planted as a living fence on the lower boundary and harvested for fuelwood and poles. Additional fuelwood was gathered from the native "espino" (Acacia cavens) growing naturally on the hillside above the property. Beneath
FIGURE 6.4 Structural layout of a small-scale intensive farming system in the coastal zone of central Chile (Altieri and Farrel 1984).
the orchard trees, herbs are grown for medicinal purposes or to keep chickens healthy, as in the case of Ruda (Ruda tracteosa). According to some campesinos the presence of this plant in the chicken yard prevents infectious poultry diseases. Hinojo (Hinojo officinalis) is allowed to grow freely in the property margins and its cane is later used to construct fences or small huts. Irrigation water is diverted from the canal passing along the upper boundary of the property. The campesinos plant willows (Salix spp.) along the canal to hold the soil down and prevent soil sliding. The penetrating root systems, along with the dense canopy from the other trees, provides soil protection on this sloping site.

**Extensive Semi-Commercial Systems.** Semi-commercial farms range from five to 20 hectares in size. These systems are also diversified, but the crop and animal combinations are designed to increase production to yield a market-able surplus. With more land, the campesino devotes much of it to more extensive activities such as pasture for livestock and grain cultivation. The additional land also affords more space for wood-producing trees. In this way, nearly all of the household requirements are provided for on the farm.

Typically, campesinos grow crops preferred by the local community for commercial purposes. These crops, however, may entail relatively high risks. Therefore they hedge against this risk by growing several less variable or risky crops, like beans, squash, potato, or corn, between rows of high-value fruit trees, like peach, cherry or apple.

Figure 6.5 shows the design of a 12-hectare farm about 10 kilometers east of Temuco, south of Chile, where the campesino balanced his farm to provide food, clothing, housing, and capital. The farm consists of an inter-planted area of annual crops and fruit trees, a mixed orchard of fruit trees, approximately five hectares of pasture, two to three hectares of wheat, and a stand of pine (Pinus radiata). He harvested 280 kg of honey from 26 beehives per year, obtained 10 to 12 liters of milk per day from three cows, collected 10 to 11 eggs per day from his chickens, and from the wheat, supplied all of his flour for making bread. Pine trees were planted to provide wood. The fast-burning wood is also used in constructing the house and barns. Guano from the animals and crop residues are collected in a compost pile for later use as fertilizer.

**Raised Field Agriculture**

Raised field agriculture is an ancient food production system used extensively by the Aztecs in the Valley of Mexico, but also found in China, Thailand, and other areas to exploit the swamplands bordering lakes.

Called chinampas in the Aztec region, these "islands" or raised platforms (from 2.5 to 10 meters wide and up to 100 meters long) were usually constructed
FIGURE 6.5 Structural layout of a twelve-hectare, semi-commercial farming system in southern Chile (Altieri and Farrell 1984).

with mud scraped from the surrounding swamps or shallow lakes. The Aztecs built their platforms up to a height of 0.5 to 0.7 meters above water level and reinforced the sides with posts interwoven with branches and with trees planted along the edges (Armillas 1971).

The soil of the platforms is constantly enriched with organic matter produced by the abundant aquatic plants, as well as with sediments and muck from the bottom of the reservoirs. A major source of organic matter today is the water hyacinth (*Eichornia crassipes*), capable of producing up to 900 kg per hectare of dry matter daily. Supplemented with relatively small amounts of animal manure, the chinampas can be made essentially self-sustaining. The animals, such as pigs, chickens, and ducks, are kept in small corrals and fed the excess or waste produce from the chinampas. Their manure is incorporated back into the platforms (Gliessman et al. 1981). On the chinampas, farmers concentrate the production of their basic food crops as well as vegetables. This includes the traditional corn/bean/squash...
polyculture, cassava/corn/bean/peppers/amaranth, and fruit trees associated with various cover crops, shrubs, or vines. Farmers also encourage the growth of fish in the water courses.

In Asia, raised field agriculture consists of livestock/fowl/fish farming systems. Aquatic vegetation is fed to animals, and in turn, their wastes are used as fertilizer for fish ponds. A common system is pig/fish farming, in which 2,000 to 5,000 kg of fish per hectare are produced every six months. There are about 60 pigs per hectare and fish are stocked at a rate of 25,000 to 30,000 per hectare (Pullin and Shehadeh 1980).

Conclusions

All traditional agroecosystems described above have proved to be sustainable in their historical and ecological context (Cox and Atkins 1979). Although the systems evolved in very different times and geographical areas, they share structural and functional commonalities (Beets 1982, Marten 1986):

- They combine species and structural diversity in time and space through both vertical and horizontal organization of crops.
- The higher biodiversity of plants, microbes, and animals inherent to these systems support production of crops and stock and mediate a reasonable degree of biological recycling of nutrients.
- They exploit the full range of micro-environments, which differ in soil, water, temperature, altitude, slope, and fertility within a field or region.
- They maintain cycles of materials and wastes through effective recycling practices.
- They rely on biological interdependencies that provide some biological pest suppression.
- They rely on local resources plus human and animal energy, using little technology.
- They rely on local varieties of crops and incorporate wild plants and animals. Production is usually for local consumption.
- The level of income is low, so the influence of noneconomic factors on decisionmaking is substantial.

Despite the onrush of modernization and economic change, a few traditional agricultural management and knowledge systems still survive. These systems exhibit important elements of sustainability, namely, they are well adapted to their particular environment, rely on local resources, are small-scale and decentralized, and tend to conserve the natural resource base. Therefore, these systems comprise a neolithic legacy of considerable importance, yet modern agriculture constantly threatens the stability of this
inheritance. The study of traditional agroecosystems can speed considerably the emergence of agroecological principles, which are greatly needed in order to develop more sustainable agroecosystems both in the industrial and developing countries. Realistically, sustainable agriculture models are needed that combine elements of both traditional and modern scientific knowledge. Complementing the use of conventional varieties and inputs with ecologically sound technologies will ensure a more affordable and sustainable agricultural production.

1. Throughout this book the terms traditional, peasant, small-scale, and small farming are used synonymously to describe systems that rely on human and animal power and on locally available resources (Wilken 1977).

2. \( LER = \frac{Px}{Kx} + \frac{Py}{Ky} \), where \( Kx \) and \( Ky \) are the yields per unit area when the crops are grown in monoculture, and \( Px \) and \( Py \) are the production of the two crop species in a polyculture (Vandermeer 1981).
Ecologically Based Agricultural Development Programs

Most developing countries' economies have gone through major economic crisis with extraordinary social and environmental costs. Despite numerous internationally and state-sponsored development projects, poverty, food scarcity, malnutrition, health deterioration, and environmental degradation continue to be widespread problems (Altieri and Masera 1993). As developing countries are pulled into the existing international order and change their policies in order to serve the unprecedented debt, governments increasingly embrace neo-liberal economic models that promote export-led growth. Despite the fact that in some countries, the model appears successful at the macro-economic level, deforestation, soil erosion, industrial pollution, pesticide contamination, and loss of biodiversity (including genetic erosion) proceed at alarming rates and are not reflected in the economic indicators. So far, there is no clear system to account for the environmental and social costs of such models.

The crisis has demonstrated that conventional development strategies are fundamentally limited in their ability to promote equitable and sustainable development (Altimir 1982, Annis and Hakim 1988). So far, the end result of most development programs has been what is termed "growth with poverty". In the realm of agriculture, modernization has proceeded in the absence of effective land distribution and research/development programs have emphasized high-input production, all factors contributing to environmental problems in the region (Redclift 1989). A major technological problem of development projects is that global recommendations frequently prove unsuitable for the conditions of specific peasant farms (de Janvry 1981). The many forms of agriculture found in Third World countries result from variations in local climate, soils, crop types, demographic factors, and
social organizations, as well as from more direct economic factors such as prices, marketing, and availability of capital and credit. What is required is an integrated approach that accounts for these complex interactions. Cropping systems and techniques tailored to specific agroecosystems result in a more fine-grained agriculture, based on appropriate traditional and improved genetic varieties and local inputs and techniques, with each combination fitting a particular ecological, social, and economic niche. However, rather than emphasizing technological packages that are site specific, the challenge is to develop agroecological technologies that offer options and benefits across a wide range of heterogeneous agricultural environments and circumstances (Figure 7.1).

Sustainable agricultural development is difficult to implement because institutional arrangements, market forces, policies, and research efforts are biased against it. A major challenge, therefore, is to create new policies that reduce the resource costs of farming and promote social and ecological sustainability. Although new policies are an important requirement for sustainable rural development (SRD) in the region, it is not enough. Other problems, such as external debt, poverty, uneven distribution of resources, lack of appropriate technologies, and international forces, constitute important obstacles to SRD. Any basic strategy for achieving SRD must address the principal development priorities of the region (Gallopin et al. 1989, LACDE 1990):

- Reduction of poverty
- Adequate food supply and self-sufficiency
- Natural resource conservation
- Empowerment of local communities and the effective participation of the rural poor in the development process

These priorities are yet to be met by most top-down nationally/internationally sponsored development approaches which do not reach the poor or solve

![Figure 7.1](image.png)

**Figure 7.1** Potential productivity and adaptability of agricultural technologies suited for a range of environmental conditions.
hunger and malnutrition problems. A major challenge is, therefore, to create a new policy framework that enhances sustainable agricultural development and conservation efforts through the promotion of agroecological technologies directed at:

1. Increasing agricultural land and labor productivity to satisfy food needs, increase rural income and curb the advancement of the agricultural frontier
2. Introducing ecological rationality in agriculture to rationalize the use of chemical inputs, complement watershed and soil conservation programs, plan agriculture according to the land-use capabilities of each region, and promote efficient use of water, forests and other non-renewable resources
3. Coordinating agricultural and environmental/economic policies related to pricing and taxing policies, land and resource distribution and access, technical assistance, and so on.

**Grassroots Approaches to Rural Development**

Failure in the top-down development approaches legitimized the role of non-government organizations (NGOs) as new actors in rural development in the Third World. Grassroots development experiences implemented at the local level by NGOs opened new roads to target the poor directly. NGOs challenged the notion that social development could only be done top-down from the state. NGOs also represent an institutional arrangement that enriches civil society by opening new spaces for social participation. The urgent need to combat rural poverty and to regenerate the deteriorated resource base of small farms stimulated a number of NGOs in the developing world to actively search for new kinds of agricultural development and resource management strategies that, based on local participation, skills, and resources, enhance productivity while conserving resources. Local farmers' knowledge about the environment, plants, soils, and ecological processes regains unprecedented significance within this new agroecological approach (Alfieri and Yurjevic 1991). Agroecology has helped NGOs to define a new agricultural approximation to the peasant production process, which is radically different from that of the Green Revolution or other high-input approaches (Table 7.1). Recognizing that in each region there is a gradient of farmers, those that are more directly linked to the market and have access to high or external inputs, has been the reference point of the Green Revolution, with the expectation that these "progressive" farmers would serve as examples to the others in a "trickle down" technology diffusion process. Considerable progress has been made with the emergence of two new evaluation procedures, rapid rural appraisal (RRA) and natural resource
<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>GREEN REVOLUTION</th>
<th>AGROECOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TECHNICAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops affected</td>
<td>Wheat, maize, rice, and few others.</td>
<td>All crops.</td>
</tr>
<tr>
<td>Areas affected</td>
<td>Mostly flatlands and irrigated areas.</td>
<td>All areas, especially marginal areas (rainfed, steep slopes).</td>
</tr>
<tr>
<td>Dominant cropping system</td>
<td>Monocultures, genetically uniform.</td>
<td>Polycultures, genetically heterogenous.</td>
</tr>
<tr>
<td>Dominant inputs</td>
<td>Agrochemicals, machinery; high dependency on external inputs and fossil fuels.</td>
<td>Nitrogen fixation, biological pest control, organic amendments, high reliance on local-renewable resources.</td>
</tr>
<tr>
<td><strong>ENVIRONMENTAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impacts and health hazards</td>
<td>Medium to high (chemical pollution, erosion, salinization, pesticide resistance, etc.). Health risks in pesticide application and pesticide residues in food.</td>
<td>Low to medium (nutrient leaching from manure).</td>
</tr>
<tr>
<td>Crops displaced</td>
<td>Mostly traditional varieties and land races.</td>
<td>None.</td>
</tr>
<tr>
<td><strong>ECONOMIC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital costs of research</td>
<td>Relatively high.</td>
<td>Relatively low.</td>
</tr>
<tr>
<td>Cash needs</td>
<td>High. All inputs must be purchased in the market.</td>
<td>Low. Most inputs are locally available.</td>
</tr>
<tr>
<td>Cash returns</td>
<td>High. Rapid results. High labor productivity.</td>
<td>Medium. Needs time to achieve highest yields. Low to medium labor productivity.</td>
</tr>
<tr>
<td><strong>INSTITUTIONAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology development</td>
<td>Quasi-public sector, private companies.</td>
<td>Largely public; large NGO involvement.</td>
</tr>
<tr>
<td>Proprietary considerations</td>
<td>Varieties and products patentable and protectable by private interests.</td>
<td>Varieties and technologies under farmer's control.</td>
</tr>
<tr>
<td><strong>SOCIOCULTURAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Research skills needed</td>
<td>Conventional plant breeding and other disciplinary agricultural sciences.</td>
<td>Ecology and multidisciplinary expertise.</td>
</tr>
</tbody>
</table>
accounting (NRA) techniques. NRA techniques incorporate environmental externalities into conventional cost-benefit analyses and can be used to evaluate the profitability of alternative agricultural production systems when natural resources are accounted for (Faeth et al. 1991). RRA techniques constitute an important step forward toward the design of alternative "bottom-up" evaluation procedures. These techniques emphasize the informal gathering and presentation of information to facilitate a participatory process between local residents and researchers. Technologies are evaluated through very general criteria addressing environmental, economic, and social concerns, as expressed by local residents (Conway and Barbier 1990).

Despite such progress, there have been only few attempts at quantifying the impacts of agroecological strategies. This reflects the lack of interest or capability of existing academic and research institutions in the region. NGOs are action- rather than research- oriented and operate with minimal funds compared to government or international institutions. Nevertheless several NGOs have engaged in modest research efforts yielding important information on how and why their techniques work, and what benefits if any they accrue. Many NGOs are also aware that they need to improve their technical and methodological capabilities. Therefore they also recognize the importance of training and capacity building at the regional level. Some working networks to support efforts (e.g., CLADES) have already emerged (Altieri and Yurjevic 1989).

NGO efforts are not free of obstacles and limitations. These organizations are also very diverse in terms of their scope, size, internal structure, and their technical expertise and social immersion. For those NGOs involved in the implementation of agroecological proposals, a major challenge is the promotion of productive alternatives that are not only ecologically sound but also economically profitable. Profitability at the household level depends not only on what peasants and NGOs can do, but mainly on the macro conditions under which the peasant production would serve as examples to others in a sort of "trickle down" technology diffusion process. Agroecologists emphasize that in order for development to be truly bottom up, it must start with those resource-poor farmers in the inferior part of the gradient (Figure 7.2).

The agroecological approach is culturally compatible since it builds upon traditional farming knowledge, combining it with elements of modern agricultural science. The resulting techniques are ecologically sound because they do not radically modify or transform the peasant ecosystem, but rather identify traditional and/or new management elements that, once incorporated, lead to optimization of the production unit. By emphasizing the use of locally available resources, agroecological technologies also become more economically viable (Altieri 1989).
In practical terms, the application of agroecological principles has translated into hundreds of NGO programs that emphasize:

- Improving the production of basic foods, including traditional food crops (*Amaranthus*, quinoa, lupine, etc.) and the conservation of native crop germplasm
- Recovering and re-evaluating peasants' knowledge and technologies
- Promoting the efficient use of local resources (land, labor, agricultural by-products, etc.)
- Increasing crop and animal diversity in the form of polycultures, agroforestry systems, integrated crop-livestock farms, to minimize risks
- Improving the natural resources base through water and soil conservation and regeneration practices
- Reducing the use of external chemical inputs, through developing, testing, and implementing organic farming and other low-input techniques

**Assessing the Impacts of the Agroecological Approach**

Despite the lack of sufficient and, in cases, reliable field data, preliminary qualitative evaluations of some NGO programs show that agroecological schemes have resulted in tangible benefits for the local populations such as enhanced food production, regeneration and improved quality of natural
resources, and higher use-efficiency of local resources (Table 7.2). The level of "success" of the above programs is commendable given the diverse socio-economic and biophysical constraints under which NGOs operate. These constraints vary from lack of access to land and low income of peasant families to biophysical limitations of the agroecosystems such as drought, frost, marginal soils, and so on. When assessing the impacts of agroecological programs, a key limitation is the absence of an appropriate methodology for evaluation and a set of socioeconomic and ecological indicators useful for judging project viability, adaptability, durability, and success. There is a critical need for indicators that provide key insights to improve, redirect, and/or expand current efforts. Such indicators should permit development projects to be contrasted in terms of enhanced productive capacity, improvements in the quality of local resources, environmental preservation, satisfaction of human needs, equity of benefits, and increase in local or regional self-reliance, among the other relevant criteria. The long-term success of these NGOs will depend on creating the right socioeconomic conditions needed for massive replicability of agroecological strategies (Altieri and Yurjevic 1991).

Despite the many advances, bottom-up grassroots development efforts in poverty alleviation have met with mixed success. A key reason is that they are attempting to counteract an environment in which their constituents have little access to political and economic resources and in which institutional biases against peasant production prevail. Grassroots development is difficult to implement where landownership is very skewed or where institutional arrangements (i.e., credit, technical assistance, etc.) and factor markets favor the large-scale farm sector (de Janvry et al. 1987). There are many policy obstacles that prevent peasants from fair competition in the market, thus limiting the chances for any agroecological strategy to be assumed at the household level. Removal of policy constraints must occur in at least three areas:

- Elimination of anti-peasant institutional biases in access to credit, research, and technical advice
- Elimination of the perennial social underinvestment in peasant communities in education, health, and infrastructure
- Elimination of subsidies to capital intensive and agrochemical based agriculture

In addition, it will be important to create a policy climate that improves the terms of trade for peasant production by providing competition to local monopolistic intermediaries and allows peasants to capture the externalities that a peasant-sustainable agriculture might produce. This change will require defining adequate tax policies to charge "free riders" taking advantage
<table>
<thead>
<tr>
<th>NGO</th>
<th>Characteristics of intervened area</th>
<th>Agroecological and socioeconomic constraints</th>
<th>Goals of the agroecological strategy</th>
<th>Technical components of the strategy</th>
<th>Impacts and/or achievements</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEMTA (Bolivia)</td>
<td>Pacajes Province, Altiplano (3,500-3,800 m.a.s.l.) Potato, cereals, andean crops, bovine/ovine cattle, alpacas</td>
<td>Frost, low soil fertility, erosion, deforestation, drought. Generalized poverty, low access to credit, public services, and markets.</td>
<td>Slow environmental degradation process and regenerate productive potential</td>
<td>Organically managed mud-built greenhouses for vegetable production. Terracing, crop rotations for erosion control. Reforestation with native species. Improvement/management of native pastures.</td>
<td>Early production of vegetables under greenhouses resulted in premium prices in nearby La Paz markets, increasing income of participating farmers.</td>
</tr>
<tr>
<td>NGO</td>
<td>Characteristics of intervened area</td>
<td>Agroecological and socioeconomic</td>
<td>Goals of the agroecological strategy</td>
<td>Technical components of the strategy</td>
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<td>Technical components of the strategy</td>
<td>Impacts and/or achievements</td>
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<tr>
<td>CETEC (Colombia)</td>
<td>Southwest of Cauca Valley (1,500 mm rainfall). Cassava, tropical fruit trees.</td>
<td>Acid and erosive soils, crop pests and diseases, weed interference. Low income, no access to credit or technical assistance. Low prices of agriculture commodities.</td>
<td>Diversify production with low-input technologies. Natural resources conservation. Alternatives to pesticides.</td>
<td>Improved cassava cropping systems. Soil conservation systems. Home gardens. Pest control with parasites and botanicals.</td>
<td>Soil erosion has been reduced and alternatives to pesticides are proving effective.</td>
</tr>
<tr>
<td>INDES (Argentina)</td>
<td>Dry subtropical area (600 mm). Cotton and subsistence crops (maize, squash, cassava).</td>
<td>Drought, high temperatures, wind erosion, low soil fertility. Poverty, unemployment, lack of credit.</td>
<td>Food self-sufficiency. Optimize use of local resources.</td>
<td>Rationalize cotton based rotations. Improve soil cover to avoid erosion. Use of adapted crop variety.</td>
<td>Diversification schemes have brought new crops into production, challenging dominance of cotton.</td>
</tr>
<tr>
<td>CET (Chile)</td>
<td>Chiloe Island</td>
<td>Frost, acid soils, phosphorous deficiency, overgrazing of pastures, genetic erosion. Poverty, marketing problems.</td>
<td>Improve and stabilize productive systems through diversification, use of local resources, rescuing of traditional varieties and technologies, and in-situ potato genetic community conservation programs.</td>
<td>More than 100 traditional potato varieties rescued, with about 56 families involved in in-situ conservation programs.</td>
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</tr>
<tr>
<td></td>
<td>Southern Chile</td>
<td>(2,000–2,500 mm rainfall). Potato, wheat, pastures.</td>
<td>Pasture-based crop rotations. Rotational grazing systems. Silvopastoral systems.</td>
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of peasants' efforts. This kind of economic policy could help create subsidies to encourage peasants to adopt sustainable practices (de Janvry et al. 1987).

Examples of Programs

Alley Cropping in Africa

In humid tropical Africa, shifting cultivation and bush fallow systems are still dominant (Chapter 6). Increasing population and the development of more sedentary agriculture has led to shortened fallows, causing a rapid decline in soil fertility and crop yields. These areas need crop systems based on the use of leguminous plant species to restore soil fertility. In Nigeria, Wilson and Kang (1981) developed a system of alley cropping, an improved fallow system in which selected leguminous shrubs or tree species are planted in association with food crops to accelerate regeneration of soil nutrients, thus shortening the fallow period. In the alley system trees and shrubs provide green manure for the companion crops and pruning materials are used as mulch and shade during the fallow to suppress weeds. Prunings also serve as animal feed, staking material, and firewood (Kang et al. 1984). Thus, alley cropping is a multiple-use system.

In these systems food crops are grown in alleys (two to four meters wide) formed by trees or shrubs. Trials where *Leucaena leucocephala* was intercropped with maize showed substantial increases in crop production. Leaf nitrogen from pruned leaves of *Leucaena* placed on or incorporated into the soil contributed a significant 23 percent increase in maize yields over the control. The single and double *Leucaena* rows added on average 100 and 162 kg of nitrogen per hectare, respectively, to the maize plants. A well-established hedgerow of *Leucaena* can produce from 15 to 20 tons of fresh prunings (5 to 6.5 tons of dry matter) per hectare with five prunings per year. Three prunings yield over 160 kg of nitrogen, 15 kg of phosphorus, 150 kg of potassium, 40 kg of calcium, and 15 kg of magnesium per hectare per year.

Alley cropping evaluations suggest that for proper stabilization of shifting cultivation systems it is necessary to allow for an effective rest or fallow, accompanied by a series of improvements during the cropping period that lessen erosion and help maintain a fertile soil.

Other attempts at stabilizing shifting cultivation systems around the world suggest the following guidelines for sustainability (NRC 1993):

1. Respect of local knowledge on cropping practices, use of local varieties, use of fire, soil management, and manipulation of the fallow period.
2. Develop systems that strictly adhere to crop and fallow practices that maintain soil fertility. The length of time required before eventually recropping an area depends on local conditions, such as rainfall, soil
conditions, and crop type, and can range from a few years to 30 or 40 years.

3. Develop and refine organic matter management practices that improve soil and water conservation during the cropping period in order to reduce fertility loss, improve crop yields, and hasten the recovery of the system during the following fallow. The key to success is to maintain a continuous ground cover at all times during the cropping cycle. This can be achieved through minimum tillage, mulching, cover cropping, and multiple cropping.

4. Diversify cropping systems to intensify the production of useful species, thus lessening the need for additional plantings. Diversification can be achieved through a variety of multiple cropping arrangements.

5. Develop managed fallow systems by intentionally introducing fallow plants that accumulate nutrients in their biomass at a faster rate than the natural fallow and permit the harvest of useful or edible materials from the second growth vegetation.

By stabilizing shifting cultivation systems at a level of production that sustains yields, meets the needs of the local people, and respects the importance of an adequate fallow, both ecological and social benefits are obtained. Soil erosion, fertility loss, and invasion by weeds are minimized, and people are more likely to remain in one location.

Promoting Integrated Agriculture Systems in Bangladesh

In projects promoted by ICLARM, (International Center for Living Aquatic Resources Management) scientists assisted local institutions in Bangladesh to develop technologies for sustainable aquaculture that are consonant with the resources of the rural households and existing farming systems. The technologies enable short-cycle aquaculture, using fish species such as silver barb (Puntius gonionotus) and Nile tilapia (Oreochromis niloticus) in seasonal (4–6 months), small (100–200 m²) waterbodies, integrated into the existing agricultural production system.

Farmers have expressed satisfaction with the integration of aquaculture and other farm enterprises and plan to continue and expand these practices. Their reasons for doing so are far more diverse and complex than money or food. Leisure and social relationships drive adoption of the system by households, as do provision of inputs for other enterprises and rapid growth of fish for quick returns. Farmers can produce fish for a fraction of the market price: US$0.12–0.30 kg⁻¹ compared to US$0.81–1.16 kg⁻¹. Some farmers with seasonal ditches as small as 170 m² can raise 25–30 kg of fish in the 4–6 months that the water is available. A pond of about 300 m² can
provide a family of six with the present annual fish consumption level of 7.9kg caput.1

This work is now helping NGOs, such as the Bangladesh Rural Advancement Committee (BRAC) and Proshika, to assist more than 30,000 fish farmers, of whom nearly 60% are women, in utilizing formerly derelict seasonal ponds and ditches. The adoption by women of integrated aquaculture not only empowers rural women, but also improves the nutrition of their families. A 98% recovery rate on credit proves its success (Lightfoot et al. 1992).

**Using Manure in Bolivian Andean Agriculture**

As in most Andean regions, the staple diet of Bolivia's rural population consists of potatoes and maize. Spanish colonization and recent agrarian reform have radically changed the Inca agricultural system. The use of imported fertilizers in potato growing is becoming more widespread, which means that potatoes are sown more frequently and the land is left fallow for less time. This in turn causes a higher incidence of nematodes and plant diseases, which leads to greater use of pesticides. Average potato production is falling despite a 15 percent annual increase in the use of chemical fertilizer. Due to increases in the cost of fertilizer, potato farmers must produce more than double the amount of potatoes compared with previous years to buy the same quantity of imported fertilizer (Augstburger 1983).

Bolivian peasants have thus become more dependent on agricultural chemicals. Members of the former Proyecto de Agrobiologia de Cochabamba, now called AGRUCO, are attempting to reverse this trend by helping peasants recover their production autonomy. To replace the use of fertilizers and meet the nitrogen requirements of potatoes and cereals, intercropping and rotational systems have been designed that use the native species *Lupinus mutabilis*. Experiments have revealed that *L. mutabilis* can fix 200 kg of nitrogen per hectare per year, which becomes partly available to the associated or subsequent potato crop, thus significantly minimizing the need for fertilizers (Augstburger 1983). Intercropped potato/lupine and potato/bean overyielded corresponding potato monocultures, and also substantially reduced the incidence of virus diseases.

In experiments conducted in neutral soils, higher yields were obtained with manure than with chemical fertilizers. In Bolivia, organic manures are deficient in phosphorous. Therefore AGRUCO recommends phosphate rock and bone meal, both of which can be obtained locally and inexpensively, to increase the phosphorous content of organic manures.
The Minka Project in Peru

A group of social scientists under the name Grupo Talpuy, funded by the Fundación de Tecnología Andina, have been studying and documenting the traditional farming practices and systems used by peasants in the Peruvian Andes (Brush 1982). Grupo's main activity consists of rescuing and recording local farming practices like mixed cropping, traditional pest control and fertilization, crop rotations, traditional crop varieties and uses of plants, which are later published in a low-cost magazine called *Minka* that is circulated throughout the rural areas (*Minka* 1981). The group also requests information from farmers, extension agents, and other people about specific topics.

Each issue of *Minka* is based on a month-long field survey of a different subject, written very simply and illustrated with drawings and graphics. Subjects have included mixed cropping, Andean crops, local herbal medicine, soil conservation, agricultural tools, and low-cost house construction. The magazine promotes the idea that many efficient technologies that originated and are used in local areas can be extended to farmers in outlying areas through the magazine. The objective is to make resources, especially knowledge, widely available. *Minka* emphasizes the importance of local resources that can be used without specialized knowledge. In this way, farmers can be selective in choosing technologies or practices that have worked for other peasants who share similar levels of capital, land base, and natural resources. Follow-up surveys by Grupo Talpuy revealed a great deal of technology adoption and exchange.

Clearly peasant-to-peasant technology extension avoids some of the detrimental effects associated with the transfer of foreign technologies (environmental degradation, disruption of subsistence patterns and social relationships). Not all traditional production components are effective or applicable, and Grupo Talpuy understands that modifications and adaptations may be necessary; however, they believe that the foundation of development must remain indigenous.

Diffusing IPM Technologies Among Small Rice Farmers

In Asia, FAO (Food and Agriculture Organization) is sponsoring grassroots IPM (Integrated Pest Management) programs for rice in eight countries: Indonesia, China, Bangladesh, India, Thailand, Vietnam, the Philippines, Sri Lanka, and Malaysia. These programs have trained hundreds of thousands of farmers in IPM methods and saved millions of dollars in pesticides, not to mention the associated health and environmental benefits (Stone 1992).
The approach consists of creating "Farmer Field Schools," which help farmers control their operations by teaching them about the rice agroecosystem. This helps them make more informed crop decisions and frees them from dependence on the agricultural extension agent.

Farmers convene at the school once a week for an entire crop cycle, 10 to 12 weeks, to identify pests and predators and study plant health, water management, and the effects of weather on pest cycles. Using this knowledge and their experience, each group manages a test plot to apply and evaluate IPM methods.

Farmers have responded with enthusiasm to the field schools. Indeed, IPM has become a social movement among rice farmers, with its techniques spreading from person to person in a manner unprecedented in other extension programs. For example, in Bangladesh, many village leaders and local officials have publicly endorsed the program. Farmers who receive IPM training spent 75 percent less on pesticides than their untrained counterparts while producing 13.5 percent more rice.

The above successes have encouraged NGOs and other activist groups to exert some influence on national pesticide policies. In 1991, the Dominican Republic responded to nine years of antipesticide campaigning by banning 20 hazardous pesticides, while in 1992, the Philippines took action to ban four of the country's most widely used toxic chemicals.

In Indonesia, the president issued a decree banning 57 of the 66 pesticides used on rice, phasing out pesticide subsidies over a two-year period and diverting some of this money to fund Indonesia's IPM program, including a major farmer education program.

An Organic Agriculture Design for the Peruvian Sierra

In the San Marcos province of Cajamarca, Peru, small farmers grow a variety of crops including maize, lentils, potatoes, olluco, wheat, cassava, beans, oats, and in the interandean valleys. Traditional agricultural systems have been drastically modified through elements of conventional farming and urban influences, creating a market-oriented monoculture agriculture which favors cash crops rather than andean crops.

Centro Idea, an agricultural NGO, has implemented an organic agriculture proposal in order to revert the above process, supporting a more appropriate rural development strategy that rescues the elements of the local traditional agriculture and ensuring food self-sufficiency as well as the preservation of natural resources (Chavez et al. 1989).

The basic aspects of the proposal are:

- Rational use of local resources, potentiation of natural resources, and intensive use of human and animal labor
• High diversity of native (Andean) and exotic crops, herbs, shrubs, trees, and animals grown in polycultural and rotational patterns
• Creation of favorable microclimates through the use of shelterbelts, and living fences and reforestation with native and exotic fruit and trees
• Recycling of organic residues and optimal management of small animals

This proposal was implemented in a 1.9 ha model farm inserted in an area with similar conditions facing the average campesino of the region. The farm was divided into 9 plots, each following a particular rotational design (Table 7.3). After 3 years of operation, field results show the following trends:

• Organic matter content increased from low to medium and high levels, and N levels increased slightly. Additions of natural fertilizers were necessary to maintain optimum levels of organic matter and nitrogen.
• Phosphorous and potassium increased in all plots.
• Crop yields varied among plots, however in plots with good soils (plot 1) high yields of corn and wheat were obtained.
• Polycultures overyielded monocultures in all instances.
• To farm 1 ha of the model farm it was necessary to use 100 man-hours, 15 oxen-hours, and about 100 kgs of seeds.

These preliminary results seem to indicate that the proposed farm design enhances the diversity of food crops available to the family, increases income through higher productivity, and maintains the ecological integrity of the natural resource base.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maize, beans, quinoa, kiwicha, squash, and chiclayo</td>
<td>Wheat</td>
<td>Barley</td>
</tr>
<tr>
<td>2</td>
<td>Barley</td>
<td>Lupinus and lentils</td>
<td>Linaza</td>
</tr>
<tr>
<td>3</td>
<td>Wheat</td>
<td>Favas and oats</td>
<td>Maize, beans, quinoa, kiwicha,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Rye</td>
<td>Wheat</td>
<td>Lentils</td>
</tr>
<tr>
<td>5</td>
<td>Lupinus</td>
<td>Maize, beans, quinoa, kiwicha, squash, and chiclayo</td>
<td>Wheat</td>
</tr>
<tr>
<td>6</td>
<td>Fallow</td>
<td>Linaza</td>
<td>Barley and lentils</td>
</tr>
</tbody>
</table>
A Sustainable System for Small Farmers in Chile

In Chile, where subsidized credit has been virtually eliminated and technical assistance to farmers privatized, the Centro de Educacion y Tecnologia (CET) is helping peasants achieve year-round food self-sufficiency at low cost. The CET approach has been to establish several half-hectare model farms that can meet most of the food requirements for a family with scarce capital and land. In this system, diversity is the critical factor in using scarce resources efficiently. Thus crops, animals, and other farm resources are assembled in mixed and rotational designs to optimize production efficiency, nutrient cycling, and crop protection (CET 1983). The farm consists of diverse combinations of forage and row crops, vegetables, forest and fruit trees and animals. The main components are:

1. Vegetables: Spinach, cabbage, tomatoes, lettuce
2. Chacras: Corn, beans, potatoes, peas, fava beans
3. Cereals: Wheat, oats, barley
4. Forage crops: Clover, alfalfa, ryegrass (ballica)
5. Fruit trees: Grapes, oranges, peaches, apples
6. Forest trees: Black locust, honey locust, willows
7. Domestic animals: One milk cow, chickens, pigs, ducks, goats, and bees

The family eats the vegetables, fruits, and chacras. Forage crops and some chacras serve as food for the animals. Forage crops can also be plowed under as green manure. Fava beans provide the protein in poultry feed. Wheat and oats are used in making bread. All plant residues and manures go into compost. Manure can be applied directly around the base of the fruit trees. Crop residues (such as wheat straw and corn stalks) can be fed to the animals or left on the soil as a stubble mulch.

Non-fruit trees are used for fodder, wood, fuel, or construction materials. The tree species black locust (Robinia pseudoacacia) is a nitrogen fixer and also produces pest-resistant wood suitable for fence posts. The foliage of honey locust (Gleditsia triacanthus) and Salix spp. can be used as fodder. Russian wild olive is also a nitrogen fixer and provides a wildlife habitat.

Seedlings are started in a solar-powered greenhouse, which consists of a big hole in the soil, three by three meters, about one and a half to two meters deep, covered by a sheet of transparent plastic. Most vegetables are produced in heavily composted raised beds. The rest of the vegetables, cereals, legumes, and forage plants are produced in a seven-year rotational system described in Figure 7.3. Relatively constant production is achieved by dividing the land into as many small fields of fairly equal productive capacity as there are years in the rotation, which amounts to about six tons per year of useful biomass for 13 different crop species. The rotation was
FIGURE 7.3 Model design of a self-sufficient farming system based on a seven year rotational scheme adaptable to Mediterranean environments (adapted from CET 1983).
designed to produce the maximum variety of basic crops in six plots, taking advantage of the soil-restoring properties of the rotation. In this way each plot receives the following treatments throughout the seven-year period (Table 7.4).

Crops can be grown in several temporal and spatial designs (such as strip-cropping, intercropping, mixed cropping, cover crops, living mulches) within each plot, thus optimizing the use of limited resources and enhancing the self-sustaining and resource-conserving attributes of the system. An important consideration in designing the rotation is the stability of the cropping systems, in terms of both soil fertility and pest regulation.

**Soil Fertility.** It is well accepted that rotating grains with leguminous forage crops provides more nitrogen and much higher yields of the subsequent grain crop than are obtained under continuous grain monocropping (Chapter 11). The output of grain will depend on how efficiently the legumes supply nitrogen. Usually a large tonnage of plant material is disked or plowed into the soil when a nitrogen-fertilizer effect is desired. The tissues incorporated into the soil must be mature. Incorporating mature straw or green manure with high carbon/nitrogen ratios at first results in the "locking up" of soluble soil nitrogen in the cells of the decomposing microorganisms. As a result, additional inputs of nitrogen may be required (Troeh et al. 1980). Studies have shown that legumes such as sweet clover, alfalfa, and hairy vetch can produce between 2.3 and 10 tons per hectare of dry matter and fix from 76 to 367 kg of nitrogen per hectare, sufficient for most agronomic and vegetable crops (Palada et al. 1983).

Manure may be applied to the plots in spring or fall. If applied in the fall it might be immobilized long enough to have a residual effect on the summer crops. Leaving wheat straw in the field might immobilize mineral nitrogen

<table>
<thead>
<tr>
<th>Crops</th>
<th>Rotations</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chacras</td>
<td>corn/beans/potato</td>
<td>Spring, summer--Year 1</td>
</tr>
<tr>
<td>Winter chacras</td>
<td>peas and fava beans</td>
<td>Fall, winter--Year 2</td>
</tr>
<tr>
<td>Vegetables</td>
<td>tomato, onion, squash, etc.</td>
<td>Spring, summer--Year 2</td>
</tr>
<tr>
<td>Supplementary pasture</td>
<td>oats, clover, ryegrass</td>
<td>Fall, winter--Year 2</td>
</tr>
<tr>
<td>Industrial crops</td>
<td>soybean, peanuts, sunflower</td>
<td>Spring, summer--Year 3</td>
</tr>
<tr>
<td>Permanent pasture</td>
<td>wheat, clover, alfalfa, ryegrass</td>
<td>Fall, winter, spring--Year 4</td>
</tr>
<tr>
<td>Permanent pasture</td>
<td>clover, alfalfa, ryegrass</td>
<td>Summer--Year 5, Fall--Year 7</td>
</tr>
</tbody>
</table>
during vegetative growth of beans in the following year, thereby stimulating nitrogen fixation in legumes. The residues decompose during the first few months, although decomposition may be slowed by an inadequate supply of nitrogen (Troeh et al. 1980). Crop residues also provide enough shade to keep the mulched soil cooler than a bare soil, a desirable effect during the summer in an area with a Mediterranean climate.

**Pest Regulation.** The rotational scheme provides nearly continuous plant cover, which aids in controlling annual weeds. In the pasture plots, underseeding wheat with clover helps keep weeds under control after the wheat is harvested. Incorporating legume cover crops in annual crops such as corn, cabbage, or tomatoes by overseeding and sod-based rotations has been shown to reduce weeds significantly (Palada et al. 1983). Although these systems may not improve crop yields when compared with clean cultivated crops, they offer great potential for hillside farmers, as they reduce erosion and conserve moisture (Chapter 10).

Crop rotation also has a profound impact on insect pest populations. For example, more corn rootworms (*Diabrotica* spp.) are found in a continuous corn monoculture than in cornfields following soybean, clover, alfalfa, or other crops. The pest has one generation per year and prefers to oviposit in cornfields. Thus, the environment for a particular pest and its natural enemies might be desirable to improve their synchrony. A compatible winter crop can be responsible for the successful overwintering of large numbers of parasites. Weeds along field margins serve a similar function. Their importance lies in the maintenance of a balance between the pest and its natural enemies during the period the crop is not available. Thus, the annual clean-up of weeds along field edges could destroy overwintering sites of important natural enemies (van den Bosch and Telford 1964).

The presence of alfalfa in the rotational scheme can enhance the abundance and diversity of predators and parasites on the farm. Strip-cutting alfalfa forces predators to move from alfalfa to other crops. Cutting and spreading alfalfa hay containing beneficial insects throughout the farm also increases natural enemy populations (van den Bosch and Telford 1964). The use of cereal residues as straw mulches in the succeeding crops can significantly reduce virus vector white fly populations (*Bemisia tabaci*) by affecting their ability to attract and alight (Palti 1981).

Infestations of fall armyworm (*Spodoptera frugiperda*) in corn and of *Empoasca* spp. (leafhoppers) and *Diabrotica* spp. (leaf beetles) in beans can be greatly reduced by interplanting both crops (Chapter 10).

Numerous long-term rotations (three to six years) have been proposed to reduce populations of pathogens in the soil, although short-term sequences can also be effective. Peas, for example, reduce *Gaeumannomyces solanacearum* populations that build up during a preceding wheat crop. Incorporating
barley straw by rototilling in the topsoil can drastically reduce populations of *Verticillium albo-atrum*. Incorporating mature legumes or hay as green manure can also affect soil fungal populations and nematodes. Rape, pea, or mixed grass legume green manures reduce populations of *Gaemannomyces graminis* in wheat by stimulating antagonists (Palti 1981).

**Evaluating the Module.** CET personnel have closely monitored the performance of this integrated farming system. Throughout the years soil fertility has improved (P205 levels, which were initially limiting increased from 5–15 ppm) and no serious pest or disease problems have been noticed. The fruit trees in the garden orchard and those surrounding the rotational plots produce about 843 kgs of fruit/year (grapes, quince, pears, plums, etc.). Forage production reaches about 18 tons/0.21 ha per year, milk production averages 3,200 lts per year, and egg production reaches a level of 2,531 units. A nutritional analysis of the system based on the production of the various plant and animal components (milk, eggs, meat, fruits, vegetables, honey, etc.) shows that the system produces a 250% surplus of protein, 80% and 550% surplus of vitamin A and C, respectively, and a 330% surplus of calcium. A household economic analysis indicates that given a list of preferences, the balance between selling surpluses and buying preferred items is a net income of US$790. If all the farm output is sold at whole prices, the family could generate a net income of US$1,637, equivalent to a monthly income of US$136, 1.5 times greater than the monthly legal minimum wage in Chile (Yurjevic 1991).

**Reaching Chilean Peasants.** Groups of farmers (especially community leaders) coming from local and distant areas live on CET's farms for variable periods of time, learning by participating in the planning, management, and evaluation of the organic production systems. After training, farmers are given a packet of the seeds they will need to set up a similar system. They return to their communities to teach their neighbors the new methods and apply the model in their own lands. Follow-up evaluations of the program revealed that many peasants have adopted some or all of the farm design. In many instances, peasants have modified the technologies according to their own lore and resources. For example, in southern Chile, a group of peasants did not use compost but instead fertilized their crops with litter from nearby *Acacia* forests, as is traditional.

**The Modular System in the Tabascan Lowlands**

Various forms of subsistence farming are known to have been employed by the original Indian inhabitants of Tabasco, Mexico, and are thought to have been highly productive (Gliessman et al. 1981). Slash-and-burn agriculture was used for basic grain production (corn, beans), whereas kitchen gardens (*huertos familiares*), composed primarily of tree crops and
their associated understory herbs, shrubs, and vines, added great variety to the local diet. Cacao was produced as an understory element in these kitchen gardens and this crop has been expanded considerably with a plantation system that uses legume shade trees.

In recent years the emphasis in agriculture in the Tabascan lowlands has been away from subsistence agriculture and toward commercial farming and stock-raising. Accompanying this shift toward commercial activities has been a gradual abandonment of traditional agricultural practices and varieties. As part of a program to reinstate the diversity and stability of productivity characteristic of the traditional agroecosystems, Gliessman et al. (1981) installed production units, referred to here as modular systems. These systems encourage the application of ecological principles to agriculture through the incorporation of the empirical knowledge present in the region.

Each production unit consists of five to 15 hectares controlled by several families as part of their other agricultural activities. Depending on the social structure of the community, the families may live in the module or may live in a nearby community (ejido) and work in the module during the day. Thus production from each module is either consumed by the families living there, or the products are distributed to the members of the ejido. Any excess in production is available for sale or exchange.

Each production unit has an outermost band of vegetation consisting primarily of second growth species present naturally in the region (Figure 7.4). This band serves simultaneously as a windbreak, a source of natural

![Diagram](image-url)

**FIGURE 7.4** Diagrammatic representation of a modular system emphasizing balancing inputs and outputs by various ecological management practices (Gliessman 1982b).
predators and parasites for biological control, and a source of firewood and building materials. At the same time these shelter belts serve as biological reserves or germplasm banks for part of the plants and animals normally present in tropical ecosystems. By selective species enrichment with forest and fruit tree species, it is possible to apply agrosilvicultural management practices, increasing the long-term value of the shelter belt.

The interior part of each modular unit is constructed on the basis of the site’s topographic diversity. Where the lowest part of the module can be centrally located, large tanks are constructed to collect the dissolved nutrients and particles of soil and organic matter in the runoff. Fish, ducks, and other aquatic animals are produced in the tanks, and the aquatic plants and sediments serve as fertilizer in other parts of the module. Frequently small canals are built radiating out from the central tank to further aid in capturing excessive runoff. To avoid total inundation of the site, a principal canal can be built to eliminate excess water, or in some cases, to add water in times of low rainfall.

Around the central tank or along the edges of the water courses, raised platforms (from 2.5 to 10 meters wide and up to 100 meters long) are constructed, often with the material extracted from the catchment basins, forming a system of "tropical chinampas" for intensive vegetable production. Chinampas are described more fully in Chapter 6.

Agriculture/Aquaculture Systems in Veracruz

In a similar Mexican project, integrated farms were established in the state of Veracruz to help farmers make better use of local resources (Morales 1984). In unique designs based on the chinampas and Asiatic aquaculture systems, vegetable production, animal husbandry, and fish production were integrated through the management and recycling of organic matter. The intensive cultivation of corn, beans, and squash for local consumption, and of high-value vegetables such as Swiss chard, cabbage, cilantro, and chiles, provided abundant plant wastes and cuttings, which were used as cattle and horse feed. All animal wastes were returned as fertilizer for the fields and fish ponds.

The Impacts of Soil Conservation Programs on the Hillsides of Latin America

Central America

Perhaps the major agricultural challenge in Latin America is to design cropping systems in hillside areas that both maintain yields and reduce erosion. One of several NGOs to take on this challenge is Loma Linda in
Honduras, who has developed a simple no-till system for crop production on steep slopes.

Initially weeds in a fallow area are cut with a machete or other appropriate tool, without soil being removed. Using a hoe or a small plow, small furrows are opened following the contour every 50–60 cms. Crop seeds and compost and/or chicken manure are placed in the furrow and covered with soil. As the crop grows, weeds are kept mowed to avoid excessive competition, with the weed biomass left within the crop row as a mulch for cover and as an input of organic matter. Excellent yields can be obtained without the use of chemical fertilizers, and more importantly, without experiencing significant soil loss (Altieri 1991).

In a similar project in Guinope, Honduras, the private voluntary organization World Neighbors, began an agricultural development and training program to control erosion and restore land fertility. The program introduced soil conservation practices such as drainage and contour ditches, grass barriers, and rock walls and emphasized organic fertilization methods such as using chicken manure and intercropping leguminous plants. In the first year, yields tripled or quadrupled from 400 kilograms per hectare to 1,200–1,600 kilograms. This tripling in per-hectare grain production has ensured the 1,200 families participating in the program ample grain supplies for the ensuing year. In the last five years, 40 other villages have requested training in the soil conservation practices (Bunch, 1988). Increased per-hectare productivity has meant that most farmers are now farming less land than previously, allowing more land to grow back to pine forest and used for planted pasture, fruit or coffee trees. The net result is that hundreds of hectares formerly used for erosive agriculture are now covered by trees.

**Andean Region**

In Peru, several NGOs as well as government agencies have engaged in programs to restore abandoned terraces and build new ones in various regions of the country. For example, in the Colca Valley of southern Peru, PRAVTIR (Programa de Acondicionamiento Territorial y Vivienda Rural) sponsors terrace reconstruction by offering peasant communities low-interest loans or seeds and other inputs to restore large areas (up to 30 has) of abandoned terraces. The main advantages of using terraces is that it minimizes risks in times of frost and/or drought, reduces soil loss, amplifies the cropping options because of the microclimate and hydraulic advantages of terraces, and improves crop yields. First year yields data from new bench terraces showed a 43–65% yield increase in potatoes, maize, and barley, compared to yields of these crops grown on sloping fields (Treacey 1989). One of the main constraints of this technology is that it is highly labor intensive. It is estimated that it would require 2,000 worker-days to complete
the reconstruction of 1 hectare, although in other areas of Peru terrace reconstruction has proven significantly less labor intensive, requiring only 350–500 worker/days/ha.

**Dominican Republic**

In the Central Cordillera of the Dominican Republic, most of its inhabitants are resource-poor farmers devoted to subsistence agriculture, activity, which combined with other social phenomena, results in soil erosion. The short-fallow, shifting cultivation *conuco itinerante* is the dominant cropping system that rarely reverts to forest, but rather, given land concentration and population pressure problems, they are converted into pasture and/or become unproductive fallows.

About ten years ago, Plan Sierra, an ecodevelopment project, took on the challenge of breaking the link between rural poverty and environmental degradation. The strategy consisted in developing alternative production systems for the highly erosive conucos used by local farmers. Controlling erosion in the Sierra is not only important for the betterment of the life of these farmers, but also represents hydroelectric potential as well as an additional 50,000 hectares of irrigated land in the downstream Cibao Valley.

The main goal of Plan Sierra's agroecological strategy was the development and diffusion of production systems that provided sustainable yields without degrading the soil, thus ensuring the farmers' productivity and food self-sufficiency. More specifically, the objectives were to allow farmers to more efficiently use local resources such as soil moisture and nutrients, crop and animal residues, natural vegetation, genetic diversity, and family labor. In this way it would be possible to satisfy basic family needs for food, firewood, construction materials, medicinals, income, and so on.

From a management point of view the strategy consisted of a series of farming methods integrated in several ways:

1. Soil conservation practices such as terracing, minimum tillage, alley cropping, living barriers, and mulching
2. Use of leguminous trees and shrubs such as *Gliricidia, Calliandra, Canavalia, Cajanus,* and *Acacia* planted in alleys, for nitrogen fixation, biomass production, green manure, forage production, and sediment capture
3. Use of organic fertilizers based on the optimal use of plant and animal residues
4. Adequate combination and management of polycultures and/or rotations planted in contour and at optimal crop densities and planting dates
5. Conservation and storage of water through mulching and water harvesting techniques
In various farms, animals, crops, trees and/or shrubs are all integrated as shown in Figure 7.5 to result in multiple benefits such as soil protection, diversified food production, firewood, improved soil fertility, and so on.

Since more than 2,000 farmers have adopted some of the improved practices, an important task of Plan Sierra was to determine the erosion reduction potential of the proposed systems. This proved difficult because most of the available methods to estimate erosion are not applicable for measuring soil loss in farming systems managed by resource-poor farmers under marginal conditions. Given the lack of financial resources and research infrastructure at Plan Sierra, it was necessary to develop a simple method using measuring stakes to estimate soil loss in a range of conucos including those traditionally managed by farmers and the "improved ones" developed and promoted by Plan Sierra.

Based on field data collected in 1988–1989, Figure 7.6 depicts the cumulative erosion rates of three traditional and one improved farming system. Although erosion rates were unacceptably high in all systems, the alternative system recommended by Plan Sierra (Conuco PMA) exhibited substantially less soil loss than the traditional shifting cultivation, cassava, and guandul monocultures. The positive performance of the Conuco PMA seems related to the continuous soil cover provision through intercropping, mulching, and rotations, as well as the shortening of the slope and sediment capture provided by alley cropping and living barriers.

The simple but effective methods of Plan Sierra to estimate soil loss under farmers' management conditions are providing data on the erosive potential of various cropping systems and the effects of soil conservation practices. In most cases, measured erosion rates conformed to the determinant factors of slope, rainfall, and soil cover. Given the ecological heterogeneity of the area in terms of soils, microclimate, and vegetation, it is difficult to generalize from the data across systems.

Re-Creating Incan Agriculture in the Peruvian Andes

In Peru, the new enthusiasm for ancient technologies also extended to the rescuing of an ingenious system of raised fields that evolved on the high plains of the Peruvian Andes about 3,000 years ago. These waru-waru, which consisted of platforms of soil surrounded by ditches filled with water, were able to produce bumper crops in the face of floods, droughts, and the killing frosts common at altitudes of almost 4,000 meters. Around Lake Titicaca, remnants of over 80,000 hectares of them can still be found.

In 1984, several NGOs and state agencies created the Projecto Interinstitucional de Rehabilitacion de Waru-Waru en el Altiplano (PIWA) to assist local farmers in reconstructing the ancient farms (Sanchez 1989). The combination of raised beds and canals has proved to have remarkably
FIGURE 7.5 Complementary interactions in diversified cropping systems resulting in enhanced soil protection, soil fertility, and biological crop protection.
sophisticated environmental effects. During droughts, moisture from the canals slowly ascends to the roots by capillary action, and during floods, the furrows drain away excess runoff. Waru-warus also reduce the impact of extremes of temperature. Water in the canals absorbs the sun's heat by day and radiates it back by night, thereby helping protect crops against frost. On the raised beds, night time temperatures can be several degrees higher than in the surrounding region. The system also maintains its own soil fertility. In the canals, silt, sediment, algae, and plant and animal remains decay into a nutrient-rich muck which can be dug out seasonally and added to the raised beds. Soil analysis conducted on samples from reconstructed waru-warus showed increased levels of nitrate nitrogen, phosphorus, and potassium as well as a pH ranging from 4.8-6.5, optimal for potato growth (Erickson and Chandler 1989).

All these environmental effects determine the higher productivity of the waru-warus, compared to that of the chemically fertilized pampa soils. In the district of Huatta, reconstructed raised fields produced impressive harvests, exhibiting a sustained potato yield of 8-14 t/ha/yr. These figures contrast favorably with the average Puno potato yields of 1-4 t/ha/yr (Erickson and Chandler 1989). In Camjata, potato yields reached 13 t/ha/yr
and quinoa yields reached 2 t/ha/yr in waru-warus reconstructed by local farmers in an area of about 12 has. with the assistance of the NGO, Centro de Investigacion, Educacion y Desarrollo (CIED).

This ancient technology is proving so productive and inexpensive that it is actively being promoted throughout the Altiplano in preference to modern agriculture. It requires no modern tools or fertilizers; the main expense is for labor to dig canals and build up the platforms. Labor requirements are highly variable ranging from 200–1,000 worker days/ha.

**Organizing Farmers for In-Situ Conservation of Native Potatoes in Chile**

The Archipelago of Chiloé, a group of islands in southern Chile, is considered one of the centers of origin of the potato *Solanum tuberosum* L. Collecting expeditions by several researchers throughout the years has determined a great diversity of native potato varieties. In 1975, Chilean botanists collected 146 different samples of native varieties, the most prevalent ones being the so-called *michunes coloradas y moradas* and the *clavelas* (Montaldo and Sanz 1962). These native varieties are highly adapted to the range of ecological conditions found in the region and are of key importance for subsistence production (Contreras 1987).

Since the early 1940s the Chilean government made several introductions of European and North American varieties (some of which had been bred from Chilotan material). In areas close to urban and market centers (especially on the big island) farmers have abandoned most native varieties and adapted these new introduced varieties such as "Desiree," "Industrie," "Condor," and "Ginecke" that now have greater commercial demand.

Not only has the introduction of new varieties contributed to the extinction of native varieties but also the diseases that came along with these varieties. Around 1950, *Phytophthora infestans* devastated most potato fields, affecting mostly native varieties that had never been exposed to the exotic pathogen and therefore lacking the necessary genetic tolerance.

In an effort to slow genetic erosion and recover some of the native potato germplasm, the Centro de Educacion y Tecnologia (CET) initiated an in-situ conservation program at its peasant training center in Notuco, near Chonchi, and in several neighboring communities.

In 1988 CET technicians surveyed several agricultural areas of Chiloé and collected hundreds of samples of native potatoes still grown by some small farmers throughout the big island. In 1989 CET established a "live" collection (garden-seed bank) of 96 native potato varieties at its Notuco center, each planted in rows of 5–10 plants in a 1/2- hectare plot area. These varieties are grown year after year and are subjected to selection and seed enhancement.

In 1990, CET technicians initiated an in-situ conservation program involving
21 farmers in five different rural communities (Dicham, Petanes, Huitauque, Notue, and Huicha). Each farmer is given a sample of five different native varieties, which they are responsible to grow within their potato fields. After harvest, farmers return part of the seed production to CET (for the garden-bank), exchange seeds with other farmers, or plant the seeds again for further reproduction of genetic material. Figure 7.7 describes the conservation and exchange dynamics of the 96 varieties maintained at CET's garden-seed bank and grown by the 21 collaborating farmers.

It is expected that more farmers will become involved in the project, and that CET will be able to select varieties based on farmers' needs and desirable characteristics. Selected varieties will be propagated and distributed among participating farmers. Excess seeds could also be sold to other farmers or exchanged for seeds of traditional varieties still not available in CET's collection. This strategy will allow a continuous supply of seeds of value to resource-poor farmers for subsistence and also will provide a repository of vital genetic diversity for future regional crop improvement programs.

**Implications for the Future**

The contemporary challenges of Third World agriculture have evolved from technical to more socioeconomic and environmental. During the 1990s the struggle against rural poverty includes two new but crucial dimensions: the ecological management of the peasants' agricultural resources and the transformation of the peasant communities into actors of their own development. To a great extent, dozens of NGOs that have been promoting grassroots approaches to rural development directed at the poorest peasants in the most diverse agroecological zones of Latin America have already incorporated these dimensions.

Analysis of most NGO projects applying agroecological concepts as a basis for their technical interventions, indicate that the proposed technologies and/or agricultural designs are highly productive and sustaining, socio-economically appropriate and culturally compatible. In marginal environments (hillsides, semi-arid areas, altiplano, etc.) the high productivity of agroecological systems, in contrast to "modern" agricultural technologies, appears to be greatly improving the resource base as well as the nutritional, and often, economic well-being of local peasant communities.

There is no doubt that, within the range of farming circumstances in the world, and given the present structure of agricultural research and extension, agroecological techniques are more appropriate and adapt and perform better than Green Revolution techniques where natural and socioeconomic resources are scarce. Evidently, the poorer the farmer is, the more relevant low-input approaches are, given that poor farmers have little choice but to use their own resources. Under improved biophysical conditions (good soils,
FIGURE 7.7 The strategy of grassroots in-situ potato genetic conservation of the Centro de Educacion y Tecnologia (CET) in Chiloé (Altieri and Montecinos 1991).
water availability) and economic conditions (credit, technical assistance), Green Revolution techniques can be more attractive to farmers, if they can out-yield agroecological strategies in the short term, or provide faster solutions to specific yield-limiting problems (Figure 7.8). This gap would not exist if low-input approaches were supported and subsidized by governments as high-input technologies have been.

Many traditional farming systems of developing countries contain a wealth of information on efficient crop production under severe resource, biological, and socioeconomic constraints. Outstanding features of these systems include their ability to bear risk, and symbiotic temporal and spatial crop mixes that often result in efficient nutrient recycling and biological pest control. The mechanisms underlying risk aversion, stable crop mixtures, sustained yields, efficient nutrient cycling, pest regulation, and other desirable features must be understood in order to incorporate them into crop systems designed for small farmers. Recommended systems should enhance the farmers' ability to cope with local and external changes, such as input prices, taxes, and government policies (Alcorn 1984).

Development projects emphasizing capital intensive, high-input technologies (mechanization, agrochemicals, imported seeds, etc.) are proving ecologically unsound, and also socially inequitable by mostly benefitting a

![Diagram](image)

**FIGURE 7.8** The potential performance of Green Revolution technologies (high-input agriculture) and agroecological technologies (low-input agriculture) along a gradient of natural resource and socioeconomic conditions affecting peasant farming systems (Altieri and Anderson 1986).
lose their autonomy as they become dependent on industry for seeds and small portion of the local populations. In promoting Green Revolution technologies in the Third World, it is important to remember that farmers other inputs. Thus, rural communities' production systems become governed by distant institutions over which they have little control (Pearce 1975).

Data demonstrating that the agroecological projects described in this chapter have improved production, income distribution, or employment have been slow to emerge, mainly because the urgencies in the field demand that more time is devoted to action than to research and publication. However, social and biological scientists must collaborate in measuring the success or failure of agroecological projects. More than an analysis of land and labor use and market participation is needed. Researchers must develop a means to measure the achievements of grassroots projects that seek to improve nutrition and well-being by food sharing and communal farming, conserving valuable natural resources and protecting peasants from displacement from their lands and from exploitation as cheap labor.

Gliessman et al. (1981) and Augustburger (1983) assessed the biological relationships and ecological stability of traditional agroecosystems and how farmers improved their total productivity. CET's farm design in Chile provides a creative example of how to assure continuous production of food by effectively organizing the limited space. The follow-up surveys have revealed that peasants adopting the recommended agricultural designs and practices experience fewer food or labor shortages, especially in areas where peasants are organized in activities that reinforce reciprocity and mutual assistance.

In summary, the few examples of grassroots, bottom-up, rural development programs described here suggest that development and diffusion of appropriate technologies for peasants must:

- Start with knowledge of peasant needs as peasants perceive them
- Use indigenous technologies
- Be village-based, involving the participation of peasants
- Emphasize local and indigenous resources (Alcorn 1984)
Organic farming is a production system that sustains agricultural production by avoiding or largely excluding synthetic fertilizers and pesticides. Whenever possible, external resources, such as commercially purchased chemicals and fuels, are replaced by resources found on or near the farm. These internal resources include solar or wind energy, biological pest controls, and biologically fixed nitrogen and other nutrients released from organic matter or from soil reserves. The specific options on which organic farming relies to the maximum extent feasible include crop rotations, crop residues, animal manures, legumes; green manures, off-farm organic wastes, mechanical cultivation, mineral-bearing rocks, and aspects of biological pest control to maintain soil productivity and tilth, to supply plant nutrients, and to control insects, weeds, and other pests (Table 8.1) (USDA 1980).

As a result, organic farming systems can differ considerably from one another because each tailors its practices to meet specific environmental and economic needs. It is, however, now widely accepted that organic agriculture does not represent a return to pre-industrial revolution methods; rather it combines traditional conservation-minded farming techniques with modern technologies. Organic farmers use modern equipment, certified seed, soil, and water conservation practices and the latest innovations in feeding and handling livestock.

The most common elements of organic farming systems are the following (Roberts 1992):
TABLE 8.1 A schematic outline of biological agriculture (after Coleman 1989).

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<th>Biological Agriculture</th>
<th>Physical Agriculture</th>
<th>Chemical Agriculture</th>
<th>Cultural Techniques</th>
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<td><strong>CULTURAL TECHNIQUES</strong></td>
<td><strong>SOIL FERTILITY MANAGEMENT</strong></td>
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**SOIL FERTILITY MANAGEMENT**

**FERTILIZERS**

**Primary Minerals**

**Organic Wastes**

**Organic Fertilizers**

**Commercial Products**
• Buildup of soil organic matter
• Elimination of potential toxic chemicals from pesticides, herbicides, and fertilizers
• Use of legumes as a prime source of nitrogen
• Application of natural fertilizers;
• Use of crop rotation to minimize pest and weed damage
• Incorporation of a diverse range of crops to gain stability
• Integration of tree crops and animals to achieve a balanced natural system
• Storage of water to use all precipitation where it falls, preventing wasteful runoff

Characteristics of Organic Farming

The most important difference between organic farming and conventional agriculture is that organic farmers avoid or restrict the use of chemical fertilizers and pesticides in their farming operations, while conventional farmers may use them extensively (Oelhaf 1978). Organic farmers do use modern machinery, recommended crop varieties, certified seed, sound livestock management, recommended soil and water conservation practices, and innovative methods of organic waste recycling and residue management.

Research programs on organic farming systems were very limited until the early 1980s. Pioneering studies of Oelhaf (1978), Lockeretz et al. (1978, 1981), Pimentel et al. (1983) and USDA (1980) on organic farming in the United States provide the most comprehensive comparison between conventional and organic agricultural systems. These studies concluded:

1. Corn yields were about 10 percent less and soybean yields were about 5 percent less on organic farms than on paired conventional farms. Under highly favorable growing conditions, conventional yields were considerably greater than those on the organic farms. However, under drier conditions, the organic farmers did as well or better than their conventional neighbors. Beyond the third or fourth year after crop rotations became established, organic farm yields began to increase, so that their yields approached those obtained by conventional methods.

2. Conventional farms consumed considerably more energy than organic farms largely because they used more petrochemicals. Also, organic farms were considerably more energy-efficient than conventional farms. The researchers found that the energy output/input ratio (or efficiency) for corn production on selected organic farms in 1974 and 1975 was 13 and 20, respectively, while for conventional farms, it was five and seven, respectively. Between 1974 and 1978 the energy consumed to produce a dollar's worth of crop on the organic farms was only about 40 percent as great as on the conventional farms. Although the organic farms had lower crop yields
than the conventional farms, their operating costs were lower by about the same cash equivalent. As a result, the net incomes from crop production on the two types of farms were about equal every year except one. The organic farmers' use of biologically fixed nitrogen and recycled organic wastes significantly reduced energy inputs in agricultural production. However, part of the increased savings from reduced use of fertilizers on organic farms may be offset by their increased use of fuel and machinery to apply manure and cultivate. A comparison of the fossil energy, labor, and extra land inputs for the production of corn, wheat, potatoes, and apples employing organic technologies and conventional technologies suggests the efficiency of energy use in both production systems varies according to the cropping system (Pimentel et al. 1983). The results indicated that organic corn and wheat production were 29 percent to 70 percent more energy efficient than conventional production. In contrast, organic techniques were 10 percent to 90 percent less energy efficient than conventional techniques to produce potatoes and apples. Insect pest and disease losses also increased when these crops were grown without pesticides.

3. Many organic farms are highly mechanized and use only slightly more labor than conventional farms. Labor requirements averaged 3.3 man-/hectares per acre on organic farms and 3.2 man/hectares per acre on conventional farms. However, when based on the value of the crop produced, 11 percent more labor was required on the organic farms because the crop output was lower (Lockeretz et al. 1978, 1981). The labor requirements of organic farmers in this study were similar to those of conventional farmers for corn and small grains, but higher for soybeans because more hand weeding was necessary. A number of other studies (Oelhaf 1978, Lockeretz et al. 1975) indicate that organic farms generally require more labor than conventional farms, but exceptions do occur. The labor required to farm organically is a major limitation to the expansion of some organic farms and an important deterrent for conventional farmers who might consider shifting to organic methods.

In many ways, organic farming conserves the natural resources and protects the environment more than conventional farming. Increased public pressure to conserve soil and water and to protect the environment has generated increased worldwide interest in organic farming practices.

More recent surveys and evaluations of organic farming includes the National Research Council's (NRC 1984) report on Alternative Agriculture and the book on organic farming by Lampkin (1992). The NRC report's main conclusions were:

1. Well-managed farming systems nearly always use less synthetic chemical pesticides, fertilizers, and antibiotics per unit of production than comparable conventional farms. Reduced use of these inputs lowers production costs and lessens agriculture's potential for adverse environmental and
health effects without necessarily decreasing, and in some cases increasing, per-acre crop yields and the productivity of livestock management systems.

2. Alternative farming practices typically require more information, trained labor, time, and management skills per unit of production than conventional farming.

3. Many federal policies discourage adoption of alternative practices and systems by economically penalizing those who adopt rotations, apply certain soil conservation systems, or attempt to reduce pesticide applications.

**Cropping Systems**

Most organic cropping systems include a legume-based rotation with green manure or cover crops (Parr et al. 1983). Guidelines for the planning of crop sequences in the rotation may include selecting a balanced range of crops which are:

- Suited to local soil type
- Grown successfully in the area
- Readily harvested by available equipment

Selecting the desired winter:summer crop ratio and planting legumes wherever soil nitrogen is low, are essential to good rotations. After legumes or fallow, high protein crops are planted. The mycorrhiza of each crop in the sequence is considered, and in temperate regions it is recommended not to recrop wheat within 5–6 years in the presence of nematodes. The usual practice is to follow a heavy green manure crop with a heavily nitrogen-demanding crop (corn, wheat, sorghum).

For example, in the corn belt, a typical rotation on organic farms would be three years alfalfa, one year corn (or wheat), one year soybeans, one year corn, one year soybeans, and then back to alfalfa. Legume forage crops provide a source of biologically fixed nitrogen for the organic system. The forage is then fed to animals rather than sold directly, thereby minimizing the flow of nutrients from the farm. Soil productivity is also enhanced by returning animal manure to the land along with crop residues.

Another example is a typical seven-season rotation involving three seasons of planting alfalfa and plowing it back into the soil, followed by four seasons of harvested crops: one of wheat, then one of soybeans, then another of wheat, and finally one of oats. The cycle would then start over. The first season of wheat growth would remove some of the nitrogen produced by the alfalfa; the soil's nitrogen reserves would be depleted much less by the soybeans, which are legumes. Oats are grown at the end of the cycle because they have smaller nutrient requirements than wheat.
Cultural Practices

Most organic farmers use disk or chisel-type implements, which mix the soil rather than invert it. They also practice shallow tillage (6-10 cm deep), which tends to retain crop residues and manures at or near the soil surface. With shallow tillage, the soil surface is protected by crop residues, promoting water infiltration and storage and reducing soil erosion and nutrient runoff. Successful organic farmers emphasize the importance of timely tillage and planting for weed control and maintenance of good soil tilth. They also use delayed planting to control weeds and to increase mineralization of organic matter and release of plant nutrients (Parr et al. 1983).

Regularly adding crop residues, manures, and other organic materials to the soil is another central feature of organic farming. Organic matter improves soil structure, increases its water-storage capacity, enhances fertility, and promotes the tilth, or physical condition, of the soil. The better the tilth, the more easily the soil can be tilled and the easier it is for seedlings to emerge and for roots to extend downward. Water readily infiltrates soils with good tilth, thereby minimizing surface runoff and soil erosion. Organic materials also feed earthworms and soil microbes (Reganold et al. 1987).

On organic farms, weeds and insects are controlled mainly with nonchemical methods, but with different degrees of effectiveness (USDA 1980). California organic growers combine cultural techniques such as cultivation, crop rotation, smother crops, trap crops, irrigation, and solarization (mulching with plastic sheets) with a balanced soil organic matter program and biological control agents to manage pests and diseases (Altieri et al. 1983a).

Weeds are usually a greater problem than insects. Organic weed control methods include crop rotations, tillage, mowing, grazing, competitive crops, intercropping, timely seeding and transplanting, intensive crop spacing, and some hand weeding. A description of weed control methods used by organic farmers in California is provided by McLeod and Sweezy (1980). In row crops, weeds are controlled both before and after planting the crop by mechanical and/or manual means. Most farmers are familiar with the life cycles of their crops, and time their cultivation to maximize stress on weeds. Cultivations are kept to a minimum. In the Anderson Valley of northern California one farmer obtained acceptable corn yields by keeping his sweet corn weed-free for only the first four weeks after crop emergence. Several vegetable and herb growers have found the Hydro-Synchron water jet transplanter to be very useful in establishing a crop stand ahead of the weeds (Altieri et al. 1983a).

Mechanical disking and/or mowing are the most common methods used to control weeds in dry-farmed orchards and vineyards. Some growers have obtained encouraging results using articulating mowers. Other growers plant
alfalfa or other types of cover as a permanent orchard cover that they mow once or twice a year (Altieri et al. 1983a).

Organic farmers have adequately controlled insects in many field crops using selective crop rotations and natural insect predators. Some farmers have experienced great difficulty in controlling insects in vegetable and orchard crops with nonchemical methods. Growers generally favor combinations of organic insecticides and biological methods of pest control (USDA 1980). Beneficial insects commonly released include green lacewings, *Trichogramma* wasps, predaceous mites, fly parasites, ladybugs, greenhouse whitefly parasite *Encarsia formosa*, mealybug destroyers, black and red scale parasites, and pink bollworm parasites, which are purchased from local insectaries.

The most common insecticides used are microbial agents, botanical insecticides, oils, soaps, and diatomaceous earth. Microbial insecticides such as *Bacillus thuringiensis* (BT), *Nosema locustae*, and *Heliothis nuclear polyhedrosis virus* (NPV) products appeal to farmers because of their selectivity. BT is used against leaf and fruit-feeding lepidopterous larvae such as tomato fruitworm, cabbage looper, diamondback moth, hornworms, codling moth, and many others. Nosema disease is used on grasshoppers. NPV is used against cotton bollworm and tobacco budworm. Using granulosis virus to control the codling moth has been tested in some organic apple orchards with encouraging results (Falcon et al. 1968). Botanical insecticides include rotenone, pyrethrum, ryania, nicotine sulfate, sabadilla, neem, quassia, and wormwood. These are preferred over synthetic chemicals because they are naturally occurring, less toxic, and break down relatively quickly in the environment.

Many farmers use dormant and summer oils to smother the eggs of various insects. Mineral oils and rotenone have been used against the codling moth in apple. Recently, soap formulations have been tried against codling moth with varied results. Most fruit growers use sex pheromone traps to monitor adult moth pest populations, or contract pest management consultants to do pest scouting and field monitoring.

Fungicides can be used to prevent diseases. These include sulfur, Bordeaux mixture, mined minerals such as copper and calcium carbonate, and other formulations made from garlic, horsetail, and hydrated lime. Orchardists find that applying a foliar spray of fish emulsion just before leaf fall aids in leaf decomposition and helps prevent outbreaks of apple scab and other diseases whose spores overwinter on leaves. Scab and powdery mildew are also prevented by applying sulfur/calcium carbonate before and during spring rains.

Most organic farmers also claim that a high proportion of humus in the soil promotes crop resistance to insect pests and plant pathogens because organically grown plants are healthier than commercially fertilized plants,
and are therefore more resistant to attack (Bezdicek and Powers 1984). Little research has been conducted to prove this claim, but Culliney and Pimentel (1986) found that late-season population densities of flea beetles, alate aphids, and caterpillars were significantly lower on collards fertilized with sewage sludge and cow manure than on chemically fertilized plants.

**Plant Nutrients and Soil Organic Matter**

The key to maintaining soil fertility in an organic system is the increased efficiency of nutrient flow from the fixed to the soluble state. Thus, organic farmers want to obtain adequate nitrogen and maintain soil organic matter at high levels to ensure maximum soil productivity. The principal source of nitrogen in organic farming systems is atmospheric nitrogen fixed by bacteria associated with legumes. In some cases, off-farm sources of manure or other organic wastes are used. Any nitrogen deficit is decreased further by residual inorganic soil nitrogen, recycling animal manures and crop residues, and mineralizing soil organic matter. Materials of low water solubility, such as rock phosphate or greensand (glauconite), are preferred sources of phosphorus and potassium, respectively. Acidulated phosphate sources are sometimes used where rock phosphate is not available.

A USDA (1980) study found that a number of organic farmers apply seaweed and fish emulsion products to the leaves of many field and vegetable crops in the hope that these products provide essential elements for plant growth and protection and increased crop yields.

Most organic farmers believe the amount of organic matter in the soil is highly correlated with soil productivity and erosion control. Thus, they frequently apply animal manures, and use green manures and cover crops to maintain the soil organic matter. Manure is sometimes composted either in wind rows or in static unaerated piles. California apple growers commonly add two tons of compost and one-half ton of limestone to their orchards per acre per year (Altieri et al. 1983a). While returning crop residues to the soil is a common practice on most farms, some farmers actually move residues from one part of the farm to another to increase the level of organic matter where needed.

Due to the great diversity in techniques, climate, soil, management practices, cropping systems, and other factors, it is often difficult to compare the nitrogen cycle for organic versus conventional farming techniques. A few general conclusions can be made, however (Power and Doran 1984):

- Organic farming techniques tend to conserve nitrogen in the soil/plant system, often resulting in a buildup of soil organic nitrogen.
- Organically managed soils have more soil microorganisms and enhanced levels of potentially mineralizable soil nitrogen.
• The net rate of mineralization of nitrogen in organic soils is often slower, resulting at times in mild nitrogen stress during periods of rapid nitrogen uptake.
• The presence of organic residues aids in reducing nitrogen losses from the organic agroecosystem.
• The effects of organic farming on the nitrogen cycle are most pronounced in the surface soil.

Case Studies of Organic Farming in California

Organic Rice Production

The best examples of organic rice production in California are the farms of the Lundberg brothers and of the Harters near Chico. The Lundbergs devote 100 acres to organic rice production in which a two-year rotation that alternates rice with purple vetch (*Vicia benghalensis*) and fallow is practiced. Dry, unsprouted rice seed is drilled directly into the soil until the appropriate moisture is available for sprouting, at which point the field is "flushed" (rapidly and briefly irrigated).

Following germination, and until the rice reaches a height of 2–4 inches, the Lundbergs allow the soil to become rather dry. When the rice begins to show stress from a lack of moisture, the field is flushed again. After the rice plants have become fully established (3–5 inches tall), the fields are kept flooded until they are drained in preparation for harvest (3–4 weeks earlier) so that the soil dries out enough to support the harvest machinery.

No crop is harvested from a field in a fallow year. Instead, purple vetch is planted in the fall following the rice harvest and again in the fall of the fallow year. The vetch normally grows rather slowly during the fall and becomes dormant during cold temperatures in winter, but by April or May it has usually produced abundant foliage that makes an excellent green manure crop or mulch. The vetch supplies about 120–130 lb of nitrogen acre⁻¹. In the spring of the fallow year, the vetch is flail-chopped and disked under, along with the largely decomposed rice straw. The field is then laser-leveled and alternately flushed and shallow-tilled with an implement to control weeds. In some years, depending on weed populations, a fallow field may be treated with as many as three cycles of flooding and tillage.

In the spring of the year in which rice is to be planted, the leguminous foliage is flail-chopped, along with the largely decomposed rice straw, leaving a mulch on the soil. A heavy no-tillage drill is then used to plant rice seed into this mulch. The drill leaves the soil bare above the narrow rows (about 8 inches apart) in which the rice seed is planted. The areas between the rice rows remain covered with the mulch, which helps control weeds.

The rationale for these management practices is based on weed and pest
control, and improved soil fertility. The mulch is thought to inhibit weed seed germination and thus compensate for the disadvantage of dry seeding (the delayed emergence of rice crops), as compared with the conventional practice. Seeding into mulch, followed by the intermittent flood in the early stages of rice growth and development, also breaks the life cycles of water pests, such as the seed midge, tadpole shrimp, and rice water weevil, which need continuous flooding to survive.

Stemrot (*Sclerotium oryzae*), a major fungal disease afflicting rice in northern California, is not a severe problem in the Lundbergs' fields because of the methods they use to expedite the decomposition of the straw and because they subsequently incorporate it into the soil. Damage by the tadpole shrimp is prevented through intermittent irrigation during the early stages of rice growth, a process that delays the anaerobic stage of irrigation (perpetual flooding), until after the rice plants have reached a height of 6-8 inches. At this stage, the tadpole shrimp do not cause injury to the rice. Major weeds such as watergrass are kept under control through rotations and cultural practices.

This organic method of rice production, which is still experimental and is currently practiced by the Lundbergs, has the advantages of breaking the reproductive cycle of various weeds and other pests and pathogens, and eliminating the use of pesticides. It has the disadvantage of significantly lowering yields (44.0 cwt acre\(^{-1}\)) and economic returns, even in comparison with statewide averages (73.5 cwt acre\(^{-1}\)) that have been adjusted for the impact of rotation (National Academy of Sciences 1989).

The Harters utilize a similar system, but instead rely on lana woolypod vetch (*Vicia dasycarpa*) for the rotation. They produce rice in only 150-200 acres each year and the remaining 500 acres of tillable soil remain planted in vetch for two years to build up soil organic matter. Although their yields are lower than in conventional systems, their profits average about $65 acre\(^{-1}\) more than the conventional farmers due to the premium price they obtain for the organic rice.

**Organic Grape Production**

The Pavichs have two organic vineyards in California: one in Delano of 467 acres and another in Kern County of 142 acres. The Pavichs apply about 2,000 tons year\(^{-1}\) of composted steer manure to their entire farm. This translates to about 2.5-3.0 tons acres\(^{-1}\) of grapes and provides approximately 94 lb of nitrogen, 85 lb of phosphorus (P\(_2\)O\(_5\)) and 138 lb of potassium (K\(_2\)O) per acre. The compost is spread by small trucks driven between the rows of vines.

For trace elements, the Pavichs rely on a special preparation, an enzyme-digested mixture of fish waste materials from a cannery, plus kelp,
which has an analysis of 5-1-1 NPK along with calcium and micronutrients. The fish material is applied as a foliar spray at least once each year, with extra applications when the vines are stressed by pests. For weed control, the Pavichs use no-tillage methods with a perennial rye grass (Lolium perenne) and native weed cover crop, chopped periodically. Hand weeding between grape vines is also used. The ground cover also supports populations of various beneficial insects that feed on pests in the vineyards.

The primary pest in their vineyards is the grape leafhopper (Erythroneura elegantula), which is often regulated by the naturally occurring parasite Anagrus. Unfortunately, this parasite is much less effective against a close relative of the grape leafhopper, the variegated leafhopper (Erythroneura variabilis), which is becoming a serious pest in fresh grapes in some parts of California.

Labor accounts for about 55% of the Pavich grape production pre-harvest costs, which total about $2.20 per box. About 3% of their grapes are sold to health food stores, for which they receive a 12–25% premium price. It is evident that this grape production operation is succeeding financially.

Conversion of Strawberry Production to Organic Management

As with many other crops in California, conventional strawberry production has confronted a series of problems. A key pest spider mite, Tetranynchus urticae Koch, has developed resistance to most registered acaricides. At the same time, regulatory restrictions affecting the availability and frequency of use of chemical controls are on the increase. Growers continue to depend on soil fumigation and the application of highly soluble inorganic nutrients. Production costs continue to rise.

However, some strawberry growers have found economic and environmental incentives that encourage them to convert their high-input production systems to practices that depend less on external inputs. These include price premiums from consumers for residue-free products, fewer regulatory restrictions on farm inputs and their off-farm impacts, and lower production costs.

The interdisciplinary research team at the University of California at Santa Cruz Agroecology Program has developed a systems-level protocol for the simultaneous, comparative monitoring of yield-affecting variables in conventional and organic conversion farm production (Gliessman 1990). They applied the protocol to a multi-year study of the process of conversion to low-input farming practices for strawberries.

Working with a small-scale strawberry grower with conventional production experience, but who has also successfully begun the transition to legally certified organic production, in the fall of 1987 researchers established annual strawberry production on a 0.5-acre plot in a randomized, complete
black-design with six replicates of two treatments: (a) conventionally recognized production guidelines recommended by the University of California Cooperative Extension; (b) management without synthetically derived inputs in accordance with the California Health and Safety Code Section 26569.11-17 and the California Certified Organic Farmers guidelines and enforcement provisions. First year results from the experiment indicated the following trends:

1. Levels of soil organic matter at a depth of 15 cm were not significantly different in the two production systems.
2. No significant differences in soil pH were observed between production systems.
3. An early season determination of soil bulk density at a depth of 10 cm indicated no significant differences between the two systems.
4. An early season test of soil percolation rates and water-holding capacities showed no significant differences between the two systems. No significant differences were seen in total and available soil nitrogen and phosphorus during the season, but significantly higher potassium levels were detected in the conversion system in the early (520 vs. 400 p.p.m.) and mid-season (486 vs. 381 p.p.m.) samples. No significant differences could be detected in cation exchange capacity.
5. At root depth, soil temperatures in the conventional production system exceeded those in the conversion system by as much as 2°C through March. The clear plastic mulch used in the conventional system warmed the soil more effectively than did the black plastic used in the conversion system.
6. Marketable fruit yield for the conversion system was 61% of that achieved in the conventionally managed plots. The earlier development of plants in the conventional production system resulted in higher fruit yields.
7. Populations of a key strawberry pest, the two-spotted spider mite (*Tetranychus urticae*), were significantly lower in the conventional system than in the conversion system for seven weeks. Mean population density in the conversion system never exceeded the economic damage threshold, estimated at 20 mites per leaflet for the winter-planted Chandler variety. Acaricides were applied three times (mid-March, early April, and early May) in the conventional production systems to control the two-spotted spider mite. Populations of the predacious phytoseiid mite (*Phytoseiulus persimilis*), an introduced biological control agent, showed a density-dependent response to the two-spotted spider mite populations from late April through May in the conversion system.
8. A significantly higher biomass of weeds occurred in the organic plots early in the season, primarily because of the absence of methyl bromide fumigation. Six weeks after planting, the organic beds were mulched with black plastic, which successfully suppressed most weed growth.
9. Soil fumigation and pesticide application made non-renewable input costs higher on conventional plots, although the organic production system required more hours of 25 horsepower tractor work for mechanical weeding. Labor costs were higher in the conversion system, especially for the additional weeding and picking time per unit of yield. The price differential for organic strawberries permitted a positive profit margin (9% less than for conventional production), despite the lower production levels.

Based on the above results, management modifications to the conversion system will be made, including the use of bed covers during the first two months after planting, increasing the amount of organic soil amendments, and releasing predatory mites for spider mite control. Researchers are also working to establish a sound management strategy for the summer fallow period between annual strawberry plantings, in order to disrupt or control populations of harmful diseases or weeds, a goal currently achieved in conventional systems by soil fumigation. This management strategy may include cover cropping, soil solarization, and soil amendments.

An important outcome of these studies is the realization that the process of converting a conventional crop production system that relies heavily on synthetic, petroleum-based inputs to a legally certifiable, low-input, organic system is not merely a process of withdrawing external inputs, with no compensatory replacement or alternative management. Considerable ecological knowledge is required to direct the array of natural flows necessary to sustain yields in a low-input system.

Conversion to Organic Farming

The process of conversion from a high-input conventional management to a low-input (or low-external input) management is a transitional process with four marked phases (Figure 8.1).

![FIGURE 8.1 Productivity trends during the phases of the organic conversion process.](image-url)
1. Progressive chemical withdrawal
2. Rationalization of agrochemical use through integrated pest management (IPM) and integrated nutrient management
3. Input substitution, using alternative, low-energy inputs
4. Redesign of diversified farming systems with an optimal crop/animal assemblage which encourages synergism so that the system can sponsor its own soil fertility, natural pest regulation, and crop productivity

During the four phases, management is guided in order to ensure the following processes:

1. Increasing biodiversity both in the soil and above ground
2. Increasing biomass production and soil organic matter content
3. Decreasing levels of pesticide residues and losses of nutrients and water components
4. Establishment of functional relationships between the various farm components
5. Optimal planning of crop sequences and combinations and efficient use of locally available resources

It is important to note that the conversion process can take anywhere from 1-5 years depending on the level of artificialization and/or degradation of the original high-input system. In addition, not all input substitution approaches are ecologically sound as it is well established that some practices widely encouraged by organic farming enthusiasts such as flame-weeding and applications of broad spectrum botanical insecticides can have serious side effects and environmental impacts. To illustrate the complexities and financial implications of the conversion process, Lampkin (1990) analyzes several models where hypothetical budgets have been prepared for several farms starting with a conventional system and working through a five year conversion period to an organic endpoint. An example provided includes a 140 ha arable farm of which 136 ha is utilizable and can be cultivated. The current conventional rotation consists of wheat, barley, and oilseed rape. No livestock are kept. This is where one of the main problems can arise with the conversion of arable farms, but in this case it has been assumed that the farmer is prepared to accept the introduction of a lowland sheep enterprise. The proposed rotation for the organic system consists of:

- Red clover/ryegrass (two years)
- Winter wheat (milling)
- Oats and peas (feed)
- Field beans
• Winter wheat (feed)
• Winter barley undersown

During the conversion, the rotation would be entered at two points: in year one with spring barley, fertilized and undersown with a short-term year ley and in year four with field beans, followed by winter wheat (which may gain a small premium as in-conversion).

The results are summarized in Figure 8.2. If currently obtainable premiums on cash crops are included, the budgets predict a substantial increase in NFI (Net Farm Income) as a result of conversion, notwithstanding the need to employ additional labor to cope with the new livestock enterprise. The sensitivity analysis, however, shows how important the premium prices are. If they are taken away, the result is a significant reduction in NFI compared with the initial, conventional situation. Premium prices for livestock have not been included, but the sensitivity analysis provides an indication of the potential impact which they, too, could have on the overall results. Investment in sheep housing and the purchase of breeding livestock, as well as the development of manure handling and storage facilities, will be required.

FIGURE 8.2 Changes in income during the conversion period on a hypothetical 140 ha arable farm.
Organic Farming and Wildlife

A trend toward organic farming would produce diversity in crop types and smaller fields, benefiting many non-game and game birds. A diversified farming habitat in South Dakota with fencerows, weeds, and marshes supported a spring population of 110 pheasant hens per section (2.59 square kilometers) compared with 21 hens per section in a simpler Nebraska habitat comprising wheat and row crops. Nesting cover, such as winter wheat, pasture, and alfalfa (*Medicago sativa*) comprised 37 percent of the total land area and produced about 63 percent of all pheasant chicks in the simpler habitat of Nebraska. Nesting cover, as oats (*Avena sativa*), pasture, alfalfa, barley (*Hordeum vulgare*), and wheat constituted about 48 percent of the land area in South Dakota and produced about 54 percent of all pheasants (Papendick et al. 1986). Enhanced populations of wildlife in agroecosystems can result in increased biological control of certain pests and provide an extra source of income and nutrition if farmers practice selective hunting.

Constraints to Organic Farming

Although most analysis suggests that organic crop production is more energy-efficient than conventional production, there are several constraints to adopting organic technologies. First, labor productivity usually averages 22 percent to 95 percent less under conventional production. Some researchers may have exaggerated labor costs by including labor input for manure hauling and spreading, but there is no doubt that labor inputs are substantially greater for organic technology. Lockeretz et al. (1981) calculated an increase of 12 percent per unit value of crop produced organically compared with conventional production, and Oelhaf (1978) calculated about a 20 percent greater labor input for organic crops. Pimentel et al. (1983) found that labor productivity was 22 percent to 53 percent less in organic wheat and corn production. Labor productivity for organically grown potatoes and apples was 61 percent to 95 percent less than under conventional production. All these studies used different methods to assess labor inputs and therefore are not fully comparable. Historically, U.S. farmers have substituted capital for labor and this trend is continuing (Buttel 1980a).

Another constraint is the availability of adequate quantities of organic fertilizer like manure (USDA 1980). For example, only about half of the farms in Iowa keep cattle, which would be a source of manure. This reflects the growing trend toward specialization in U.S. agriculture (Pimentel et al. 1983).

A study by Blobaum (1983) concluded that several obstacles discourage conventional farmers from adopting organic methods. Organic farmers perceive the lack of access to reliable organic farming information as a serious barrier to conversion. Most rely primarily on information from other
organic farmers and from such nontraditional sources as books and magazines, representatives of organic fertilizer companies, and workshops and conferences. Organic farmers have a strong interest in research on many problems, including the need for better weed control practices. Most farmers would adopt new practices if more research-substantiated information were available.

Blobaum also found that organic farmers who use special markets are dissatisfied with problems such as small orders, long delays in getting paid, inadequate returns for cleaning and bagging grains, confusing certification standards, difficulty in contacting buyers, and the expense of maintaining special on-farm storage areas. Credit discrimination is seen as a potential problem by a sizable number of organic farmers. Problems with credit access, to the extent they exist, appear to involve government farm credit agencies.

The long-term economic benefits of organic agriculture may not be evident to a farmer faced with having to meet payments on annual production loans. Many conventional farmers are greatly in debt, partly because of heavy investments in specialized machinery and other equipment, and their debt constrains the shift to more sustainable methods. To date, society has neither rewarded farmers financially nor given them other incentives for choosing organic methods that would benefit the public. A comprehensive list of constraints on the adoption of organic farming is shown in Table 8.2.

### TABLE 8.2 Obstacles to organic farming (after Youngberg 1980).

- Limiting phosphorus and potassium
- Organic sources of plant nutrients are limited
- Restrictions on symbiotic N-fixation as a source of N
- Low-solubility nutrient sources
- Limited demand for organic food
- Lack of organized marketing
- Increased transportation costs through geographical dispersion of producers
- Reduced production
- Low income crops in rotational systems
- Economic loss during transition from conventional to organic farming
- Greater risks from weeds and insects
- Increased costs of labor
- The need to maximize economic return
- Lack of credit and financing
- Lack of communication and understanding
- Attitudinal barriers and inadequate knowledge about the benefits of organic farming
- Ambiguity of organic farming concepts
- Lack of information on organic farming
- Lack of adaptable crop varieties
Implications of Large-Scale Organic Farming in the United States

Langley et al. (1983) used a model to estimate how a complete transformation of U.S. agriculture to organic practices would affect production, supply prices, land use, farm income, and export potential. Crop yields and production costs were estimated for 150 producing regions for seven crops under both conventional and organic methods. The study concluded that a complete transformation would easily allow the nation to produce enough crops for domestic consumption; however, it would also be necessary to reduce U.S. exports. Net income of the U.S. farm sector would be higher under organic farming because of lower costs of production and higher crop supply prices, but these prices would raise the cost of the domestic food supply. The lower level of production with organic farming methods also implies that the nation's productive reserve would be reduced, which could lead to some shortages in years of relatively poor growing conditions either domestically or abroad. Using net income as a criterion indicates that only the Southeast and southern plains would encounter losses under organic farming.

More recent economic evaluations suggest that profits from organic farms can exceed those of conventional farms. The cash incomes per acre for the two types of farms were comparable over two years, but because the input costs of sustainable agriculture are lower, its net returns are 22.4 percent higher. Variable costs include those for fuel, machinery maintenance, seed, fertilizer, pesticide, and labor. Among the fixed costs are property taxes and interest on loans (Figure 8.3).

Cuba: A Nationwide Conversion to Organic Agriculture

Since Cuba's trade relations with the socialist bloc collapsed in 1990, pesticide imports dropped by more than 60%, fertilizers by 77%, and petroleum for agriculture dropped by 50%. Suddenly, an agricultural system almost as modern and industrialized as that of California was faced with a tremendous challenge: the need to double food production and reduce inputs by half and at the same time maintain export crop production so as not to further erode the country's desperate foreign exchange position.

Since 1989, the Cuban government has adopted the policy to promote a new science of agriculture more in tune with the scarce resources and the need for food self-sufficiency. Cuba's new research directions heavily emphasize understanding and exploiting the subtle yet powerful abilities of biological organisms to perform many of the tasks previously done by synthetic chemicals. Biologically based or derived fertilizers and biological control of pests are at the heart of this new quest for biologically sophisticated management of agroecosystems (Rosset and Benjamin 1993).
The policy objectives during this special period, to achieve a low petro-
chemical input sustainable agriculture without reducing yields, have 
required a major reorganization in the structure of agricultural research and 
extension in Cuba and the flow of information. The de-emphasis of capital-
and energy-intensive technologies requires new relationships between 
scientists, extension agents, and farmers. The pre-existing role of scientists 
as generators of innovative technological packages and of extension agents 
as conduits of their delivery to farmers is clearly changing in favor of a 
partnership between the three in the development and dissemination of new 
aricultural approaches.

Cuban scientists have become increasingly reliant on farmer innovation 
and experimentation for research directions that complement their efforts to 
develop promising organic farming practices as well as to adapt techniques 
developed outside the country. They are emphasizing technologies recovered 
or developed at the local level that have widespread applicability, which 
extension agents and scientists disseminate over a broader region, and 
low-input technologies utilized in other countries, which are promoted for 
local experimentation and adoption.

One of the keys to Cuba's new model of agriculture is to find ways to 
reduce chemical use for management of plant diseases, insect pests, and
weeds. The most interesting aspect of contemporary insect pest management efforts in Cuba are the Centers for the Production of Entomophages and Entomopathogens (CREEs) where decentralized, "artesanal" production of biocontrol agents takes place. Despite limited resources, the government has invested its capital in construction and operation of these centers. By the end of 1992, 218 CREEs had been built throughout Cuba to provide services to state, cooperative, and private farmers.

The centers produce a number of entomopathogens (Bacillus thuringiensis, Beauvaria bassiana, Metarhizium anisopliae, and Verticillium lecanii), as well as one or more species of Trichogramma, depending on the crops grown in each area. CREEs are maintained and operated by local technicians (Table 8.3).

Cuban scientists are also pursuing several other lines of research in developing alternatives to conventional insecticides, including work on parasitic nematodes and plant-derived pesticides. A program to develop reliable and cost-effective methods for the production and field application of several species of nematodes that attack insects is currently under way; however, mass production is still in the developmental stages.

Scientists are also screening a large number of plants for insecticidal, fungicidal, bactericidal, and herbicidal qualities. In addition to these screening efforts, applied work has been initiated on the cultivation and production of two species of plants with known insecticidal qualities, neem and Melia. Small plantations of neem and Melia have been started and research on formulations and application methods is advancing.
TABLE 8.3 Biological organisms for the control of insect pests in Cuba.

<table>
<thead>
<tr>
<th>Organism</th>
<th>Crop</th>
<th>Target Pest</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Bacillus thuringiensis</em></td>
<td>collards</td>
<td><em>Pieris</em> sp.</td>
</tr>
<tr>
<td></td>
<td>tomatoes</td>
<td><em>Heliothis</em> and <em>Spodoptera</em></td>
</tr>
<tr>
<td></td>
<td>watercress</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pepper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cassava</td>
<td><em>Erynnis</em> sp.</td>
</tr>
<tr>
<td></td>
<td>yucca</td>
<td><em>Spodoptera</em></td>
</tr>
<tr>
<td></td>
<td>sweet potato</td>
<td><em>Spodoptera</em></td>
</tr>
<tr>
<td></td>
<td>potato</td>
<td><em>Heliothis</em></td>
</tr>
<tr>
<td></td>
<td>corn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tobacco</td>
<td></td>
</tr>
<tr>
<td><em>Beauveria bassiana</em></td>
<td>banana</td>
<td><em>Cosmopolites sordidus</em></td>
</tr>
<tr>
<td></td>
<td>sweet potato</td>
<td>Curculionidae (weevils)</td>
</tr>
<tr>
<td></td>
<td>rice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>citrus</td>
<td></td>
</tr>
<tr>
<td><em>Metarhizium anisopliae</em></td>
<td>grasses</td>
<td><em>Cercopidae</em> (spittlebug)</td>
</tr>
<tr>
<td></td>
<td>rice</td>
<td>Curculionidae</td>
</tr>
<tr>
<td></td>
<td>citrus</td>
<td></td>
</tr>
<tr>
<td><em>Paecilomyces lilacinus</em></td>
<td>guava</td>
<td>Nematodes of the genus</td>
</tr>
<tr>
<td></td>
<td>coffee</td>
<td><em>Meloidogyne</em></td>
</tr>
<tr>
<td></td>
<td>banana</td>
<td><em>Meloidogyne</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nematodes, mainly</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Radopholus similis</em></td>
</tr>
<tr>
<td><em>Verticillium lecanii</em></td>
<td>tomatoes</td>
<td>whiteflies</td>
</tr>
<tr>
<td></td>
<td>pepper</td>
<td>whiteflies</td>
</tr>
<tr>
<td></td>
<td>cucumber</td>
<td>whiteflies</td>
</tr>
<tr>
<td></td>
<td>squash</td>
<td>whiteflies</td>
</tr>
<tr>
<td></td>
<td>potato</td>
<td>whiteflies</td>
</tr>
<tr>
<td></td>
<td>beans</td>
<td>whiteflies</td>
</tr>
<tr>
<td><em>Trichogramma</em> sp.</td>
<td>grasses</td>
<td><em>Mocis</em> sp.</td>
</tr>
<tr>
<td></td>
<td>cassava</td>
<td><em>Erynnis</em> sp.</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>sugarcane</td>
<td>sugarcane borer</td>
</tr>
<tr>
<td><em>Pheidole megacephala</em>,</td>
<td>sweet potato</td>
<td>weevil</td>
</tr>
<tr>
<td>(ant)</td>
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<td></td>
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</tbody>
</table>
PART THREE

Alternative Production Systems

In general terms, crop production can be increased by expanding the area planted to crops, by raising the yield per unit area of individual crops (usually by increasing input use) or by growing more crops per year in time and space.

Whatever strategy is used, crop yield \( (Y) \) is influenced by management \((M)\), environment \((E)\), and the genotype \((G)\) of the crop (Beets 1982, Zandstra et al. 1981): \( Y = f(M, E, G) \)

Management includes the cropping arrangement in time, space, and cultural techniques. Environment comprises soil and climate variables modifiable through management. The crop genotype is inherent to the crop variety chosen and its adaptive range. Using this concept, three main strategies to augment the yield of individual crops can be recognized. The applicability of each strategy will depend mainly on the availability of technical skills and capital relations (cost of inputs and prices for crops).

Although during the last decades greater emphasis has been placed on increasing yields per unit area through the use of labor-saving technologies (mechanization) and land-saving technologies (fertilizer, pesticides), recently agricultural scientists have become aware that it is important, not only to increase food production, but to do so with the most efficient use of energy and nonrenewable resources (Wittwer 1975). Some promising approaches to agricultural technology, although valuable, have been based only on a single crop production process and have not considered the whole ecosystem. Table III.1 provides a list of recommended and/or experimental practices for energy-efficient production.

For the most part, the more integrated approaches are directed toward enhancing photosynthetic efficiency and crop growth through (a) improving plant architecture, using \( \text{C}_4 \) plants or varieties with a high leaf-area index, adopting efficient planting patterns, and hormonal stimulation of net photosynthesis; (b) improving soil management through minimum tillage, living legume mulches, cover cropping, manures, enhancement of biological \( \text{N}_2 \) fixation, and use of mycorrhizae; (c) managing water more efficiently.
through drip irrigation, mulching, and windbreaks; and (d) managing pests in an ecologically sound manner. These technologies propose minor changes in one or two components of the system, leaving the structure of the monoculture unchallenged, but without these minor changes, realistic progress cannot be made in the development of sustainable agroecosystems.

However, if the management boundaries are expanded beyond the direct object of control (i.e., a pest problem, soil nutrient deficiency, weed infestation) a whole new set of management and design options emerges (Edens and Koenig 1981). Of special relevance are those manipulations that can simultaneously affect several components of the system. For example, growers who adopt novel agronomic systems (multiple cropping or agroforestry systems) can achieve several crop management objectives simultaneously and sometimes require little if any fertilizer or pesticides. By interplanting wild heliotrope (*Heliotropium europaeum*) within leguminous crops, weed populations have been reduced about 70 percent and the abundance of several insect pests reduced below an economic threshold as well (Putnam and Duke 1978). French and African marigolds were introduced in fields of certain crops, populations of nematodes were effectively controlled, and the germination of weeds such as morning glory, pigweed, and Florida beggarweed was also partially inhibited (William 1981). Adaptations such as these provide a new context for agroecosystem management in which system stability depends on manipulating the ecological assemblage in fields to promote biotic interactions and synergisms that benefit farmers (Altieri et al. 1983b). In the following chapters, the most relevant ecological and agronomic features of five alternative production systems are described.
TABLE III.1 Some agricultural technology approaches to reduce energy inputs into food production systems (expanded from Wittwer 1975).

<table>
<thead>
<tr>
<th>Enhancement of photosynthetic efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement of plant architecture for better light interception (i.e., leaves with vertical orientation)</td>
</tr>
<tr>
<td>Genetic selection of varieties with greater efficiency (i.e., high leaf area index)</td>
</tr>
<tr>
<td>Reduction or inhibition of photo respiration and/or night respiration</td>
</tr>
<tr>
<td>Use of varieties having a more prolonged growth period</td>
</tr>
<tr>
<td>Artificial enrichment with CO₂</td>
</tr>
<tr>
<td>Hormonal stimulation of net photosynthesis</td>
</tr>
<tr>
<td>Hormonal stimulation of crop senescence</td>
</tr>
<tr>
<td>Genetic incorporation of C₄ or CAM mechanisms into C₃ crops</td>
</tr>
<tr>
<td>Efficient planting patterns (orientation of rows N-S)</td>
</tr>
<tr>
<td>Use of plastic mulches that reflect light back to underside of leaves</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environmental modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind modification with windbreaks and shelter belts</td>
</tr>
<tr>
<td>Frost control with windbreaks, heaters, fans, and irrigation</td>
</tr>
<tr>
<td>Control of soil temperatures through mulching or application of black charcoal and asphalt</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genetic selection of crops tolerant to nutritional deficiencies or toxicities</td>
</tr>
<tr>
<td>Application of fertilizers at lower rates and increasing the efficiency of applied fertilizers</td>
</tr>
<tr>
<td>Minimum or reduced tillage</td>
</tr>
<tr>
<td>Use of manure, compost, cover crops, and green manures</td>
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<tr>
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<td>Preventative actions: resistant varieties, manipulation of crop planting date, tillage and row spacing, crop rotation, improved field hygiene, use of attractants, pheromone traps, crop diversification, etc.</td>
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<td>Suppressive actions: sterile male technique, sex-attractant pheromones, microbial and botanical insecticides, use of mechanical or fire removal, of behavioral changes, pesticidal controls when economic, etc.</td>
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TABLE III.1 continued

Disease management
Resistant varieties, crop rotations, use of sub-optimal fungicide doses, multi-lines or variety mixtures, biological control with antagonists, multiple cropping and reduced tillage

Weed management
Design of competitive crop mixtures, rapid transplant of vigorous crop seedlings to weed-free bed, use of cover crops, narrow row spacings, crop rotation, keeping crop weed-free during critical competition period, mulching, cultivation regimes, and allelopathy

Agronomic systems
Multiple cropping systems: intercropping, strip cropping, ratoon cropping, relay cropping, mixed cropping, etc.
Use of cover crops in orchards and vineyards
Sod strip intercropping and vegetable living-mulch system
Agroforestry systems
Cropping systems analog to the natural secondary succession of the area
Polyculture Cropping Systems

*Matt Liebman*

In many areas of the world, particularly in developing countries, farmers often grow crops in mixtures (polycultures or intercrops) rather than single-species stands (monocultures or sole crops). Until about 20 years ago, the characteristics of polycultures that make them desirable were generally ignored by agricultural researchers. Recently, however, polyculture research has increased and many of the potential benefits of these systems are becoming evident.

An enormous variety of polycultures exists, reflecting the wide variety of crops and management practices that farmers throughout the world use to meet their requirements for food, fiber, medicine, fuel, building materials, forage, and cash. Polycultures may involve mixtures of annual crops with other annuals, annuals with perennials, or perennials with perennials. Cereals may be grown in association with legumes, or root crops may be grown in association with fruit trees. Polycultures may be sown in spatial patterns ranging from simple mixtures of two crops in alternate rows to complex assemblies of a dozen or more intermingled species. Component crops of polycultures may be planted at the same date or at different dates (relay cropping); harvests of the components may also be simultaneous or staggered. Descriptions of different polyculture systems are given by Papendick et al. (1976), Kass (1978), ICRISAT (1984), Beets (1982), Gomez and Gomez (1985), Steiner (1984), Francis (1986), and others.

The Prevalence of Polycultures Around the World

Polyculture cropping systems are important parts of the agricultural landscape in many areas of the world. They constitute at least 80 percent of
the cultivated area of West Africa (Steiner 1984) and predominate in other areas of Africa as well (Okigbo and Greenland 1976). Much of the production of staple crops in the Latin American tropics occurs in polycultures. More than 40 percent of the cassava, 60 percent of the maize, and 80 percent of the beans in that region grow in mixtures with each other or other crops (Francis et al. 1976, Leihner 1983).

Polycultures are very common in areas of Asia where upland rice, sorghum, millet, maize, and unirrigated wheat are the staple crops (Aiyer 1949, Harwood and Price 1976, Harwood 1979a, Jodha 1981). Lowland (flooded) rice is generally grown as a monoculture, but in some areas of Southeast Asia farmers build raised beds to produce dryland crops amid strips of rice (Suryatna 1979, Beets 1982).

Although polycultures are prevalent in tropical areas where farms are small and farmers lack capital or credit to purchase synthetic fertilizers, pesticides, and field machinery, their use is not restricted to such areas. Polycultures can also be used on relatively large, highly mechanized, capital-intensive farms in temperate areas. Examples include forage grasses and legumes interseeded into a growing crop of maize, soybean, barley, oats, or wheat (Stewart et al. 1980, Vrabel et al. 1980, Hofstetter 1984, Scott et al. 1987, Hattl 1989, Samson et al. 1990, Power et al. 1991, Wall et al. 1991, Hesterman et al. 1992, Kunelius et al. 1992); soybean interseeded into a growing crop of wheat (Reinbott et al. 1987); field pea planted in mixture with small grain for seed or forage production (Johnston et al. 1978, Murray and Swenson 1985, Izaurralde et al. 1990, Chapko et al. 1991, Hall and Kephart 1991); soybean strip cropped with maize or sunflower (Radke and Hagstrom 1976, Francis et al. 1986); grasses and legumes planted as understory vegetation in fruit and nut orchards (Altieri and Schmidt 1985, Bugg and Dutcher 1989, Bugg et al. 1990); and grass/legume mixtures for forage production (Heath et al. 1985).

**Yield Advantages**

One of the major reasons that farmers throughout the world choose to use polycultures is that frequently more yield can be harvested from a given area sown in polyculture than from an equivalent area sown in separate patches of monocultures. This increased land-use efficiency is particularly important in areas of the world where farms are small because of socioeconomic conditions and where crop production is limited to the amount of land that can be cleared, prepared and weeded (by hand) in a limited amount of time.

The increased land-use efficiency of a polyculture common in India, sorghum with pigeon pea, is illustrated by data from experiments conducted by Natarajan and Willey (1981). These researchers found that 0.94 hectares of sorghum monoculture and 0.68 hectares of pigeon pea monoculture were
needed to produce the same quantities of sorghum and pigeon pea that were harvested from a 1.0-hectare polyculture. The land equivalent ratio (LER) of the polyculture was thus $0.94 + 0.68 = 1.62$ (see Mead and Willey 1980) for more information about the LER concept). In this case, the yield of each crop species in the mixture was reduced by competition from the associated crop, but total yield of the polyculture, on a unit area basis, was 62 percent greater than for the monocultures.

A polyculture produces more combined yield in a given area than could be obtained from monocultures of the component species whenever $LER > 1$. LER values reported from experiments with a variety of polyculture systems indicate that substantial increases in land use efficiency are possible: 1.26 for millet/groundnut (Reddy and Willey 1981), 1.38 for maize/bean (Willey and Osiri 1972), 1.53 for millet/sorghum (Andrews 1972), 1.67 for maize/pigeon pea (Dalal 1974), 1.85 for barley/fava bean (Martin and Snydor 1982), 2.08 for maize/cocoyam/sweet potato (Unemma et al. 1985), and >2.51 for cassava/maize/groundnut (Zuofa et al. 1992). In the latter case, an LER value was calculated only for the cassava and maize components; yield of the intersown groundnut crop was extra. Thus, >2.51 hectares of monocultures were required to produce the same amount of food that the polyculture produced on 1.0 hectare.

Although farmers often use polycultures without applying fertilizers or pesticides, polyculture yield advantages are not restricted to low-input conditions. High LER values have been reported when large quantities of fertilizers and pesticides have been used (Osiri and Willey 1972, Willey and Osiri 1972, Bantilan et al. 1974, Cordero and McComull 1979). This is important because it suggests that farmers may continue to exploit the increased land-use efficiencies of polycultures as the productivity of their farming systems improves.

Some researchers have argued that high land-equivalency values for mixtures of crops with very different maturation times inflate the apparent efficiency of using polycultures, since several short-duration crops might be grown sequentially over the same period of time as a polyculture. These criticisms do not seem to be fully justified, since farmers often need to produce both long-season and short-season crops that can only grow well at certain times of year, even with irrigation (Balasubramanian and Sekayange 1990). Moreover, polyculture yields evaluated in terms of both spatial and temporal efficiency can still show advantages over monocultures (such as bean/cassava, Lehner 1983; maize/cassava, Wade and Sanchez 1984; maize/pigeon pea, Dalal 1974, Ofori and Stern 1987; maize/soybean, Dalal 1974, Ofori and Stern 1987; maize/sweet potato/bean, Balasubramanian and Sekayange 1990).

In the future, assessments of polyculture performance may include several different criteria, including caloric and protein production per hectare per
day (Wade and Sanchez 1984). These indices more closely approximate the criteria used by farmers for choosing cropping systems best able to provide a diverse, nutritious diet and marketable materials. It is also important to note that in many cases farmers are interested primarily in the yield of a main crop into which other species are sown for insurance against crop failure, minor economic uses, erosion control, soil fertility improvement, weed control, or other purposes. In this situation, yield advantage of the polyculture clearly occurs when yield of the main crop is equivalent or higher in the mixture as compared to a monoculture. For example, Obiefuna (1989) reported that interplanting egusi melon into plantain could increase plantain yields up to 26 percent. Abraham and Singh (1984) noted that interplanting fodder cowpea into sorghum increased sorghum seed yield an average of 95 percent.

Net economic returns from polycultures can be higher than from monocultures grown over equivalent areas. Norman (1977) studied cropping systems in northern Nigeria and found that when the cost of labor was included in his analyses, profitability was 42 percent to 149 percent higher for polycultures than for monocultures. Leihner (1983) found that in Colombia more labor was required for cassava/bean polycultures than for sole-cropped cassava, but that net incomes from the polycultures were higher. In experiments conducted in England, Salter et al. (1985) found that interplanting brussels sprouts with cabbage could provide higher gross margins and lower input costs per unit of produce than monocultures.

It should be noted that profitability of cropping systems can change substantially from year to year. Sanders and Johnson (1982) reported that in one year, monoculture bean systems were more profitable than maize/bean polycultures, but in the following year, when prices of the two crops changed, the relative profitabilities of the two systems were reversed. Thus, the economic performance of polyculture systems needs to be investigated over more than just a few cropping seasons.

**Yield Stability**

In farming systems where subsistence is the primary objective, reducing the risk of total crop failure appears to be at least as important as increasing potential nutritional and cash returns (Lynam et al. 1986). Yield variability of cereal/legume polycultures can be lower than for monocultures of the components, as found for wheat/legume and oat/legume mixtures in Greece (Papadakis 1941) and for sorghum/pigeon pea mixtures in India (Rao and Willey 1980). Thus, the likelihood of having nothing to eat or sell is apparently less when crop mixtures are used. Indeed, Trenbath (1983) has shown that for a given land area, the probability of a family failing to produce enough calories for subsistence is lower when the area is sown to a
sorghum/pigeon pea polyculture than when it is sown to monocultures of
the same components. Francis and Sanders (1978), working with maize and
beans, and Rao and Willey (1980), working with sorghum and pigeon pea,
found that the probability of exceeding a specified "disaster income level"
was greater for polycultures than for monocultures.

Trenbath (1976) and Burdon (1987) have suggested that yield compensa-
tion may occur between polyculture component crops, such that failure of
one component due to drought, pests, or other factors might be offset by
increased yield of the other component(s). Kass (1978) cited a study by
Gliemeroth (1950) illustrating this principle. When oat stands were reduced
due to an attack by wireworms, the yield of peas sown with oats was greater
than the reduction in the oat yield; oat yield was reduced by one-half while
pea yield increased fourfold. There is a general lack of other data that con-
clusively demonstrates this type of compensation phenomenon (Harwood
1979b, Burdon 1987). Much more research is needed before increased yield
stability can be assumed to be a general characteristic of polycultures; in
cases where stability does increase, more research is needed to understand
the causal mechanism(s).

Resource Use

As researchers direct attention toward patterns of crop growth and
resource use in polycultures and monocultures, it is becoming clear that yield
advantages of polycultures are often correlated with use of a greater propor-
tion of available light, water, and nutrients (greater resource capture) or by
more efficient use of a given unit of resource (greater resource conversion
efficiency) (Willey 1990). These improvements in resource use reflect three
phenomena: complementarity in resource use, interspecific facilitation, and
changes in resource partitioning.

If crops differ in the way they use environmental resources when grown
in monocultures then, when grown together, they can complement each
other and make better combined use of resources than when they are grown
separately (Vandermeer 1989, Willey 1990). In ecological terms, comple-
mentarity minimizes niche overlap among associated species and thus
minimizes resource competition. Complementarity may be regarded as
temporal, where crops make their major demands on resources at different
times; spatial, where canopies or roots capture resources in different zones;
or physiological, where biochemical differences exist between crops in their
responses to environmental resources.

When total crop densities are higher in polycultures than in monocultures,
polycultures can intercept more light early in the growing season. This
phenomenon has been observed in mixtures of maize with mung bean,
groundnut, or sweet potato (Bantilan et al. 1974), and sorghum with cowpea,
mungbean, groundnut, or soybean (Abraham and Singh 1984). Polycultures composed of crops with nonsynchronous patterns of canopy development and different maturation times (such as sorghum/pigeon pea mixtures, as studied by Natarajan and Willey 1980) can display a greater amount of leaf area over the course of the growing season and intercept more light energy than monocultures.

The greater amount of canopy cover produced by polycultures can decrease penetration of sunlight to the ground surface so that a greater proportion of available soil water is channeled through the crops as transpiration, rather than being lost as evaporation from the soil; Reddy and Willey (1981) observed this with millet/groundnut mixtures. Increased canopy coverage by polycultures can also increase penetration of rainfall into the soil and decrease soil erosion by lessening the impact of rain on the soil surface, such as with maize/cassava mixtures (Lal 1980) and maize/red clover mixtures (Wall et al. 1991).

Polycultures composed of species with spatially complementary rooting patterns can exploit a greater volume of soil and have greater access to relatively immobile nutrients like phosphorus (O'Brien et al. 1967, Whittington and O'Brien 1968). Polycultures composed of species that have temporally complementary patterns of root growth and nutrient uptake can capture more nutrients than monocultures if these nutrients are being made available continuously through mineralization. Natarajan and Willey (1980) observed this phenomenon with sorghum/pigeon pea mixtures, as did Reddy and Willey (1981) with millet/groundnut mixtures.

Physiological complementarity can occur in polycultures composed of species that use \( \text{C}_4 \) and \( \text{C}_3 \) photosynthetic pathways. The former type of species is often better adapted to high light environments, such as at the top of mixed crop canopies, while the latter type of species is better adapted to more shaded understory conditions (Willey 1990). Common \( \text{C}_4/\text{C}_3 \) mixtures include maize/bean, sorghum/pigeon pea, and millet/groundnut. Physiological complementarity can also exist with regard to nitrogen nutrition. Fixation of atmospheric nitrogen by legume components of polycultures to satisfy their own requirements may spare soil nitrogen supplies for use by associated non-legume components (deWit et al. 1966, Martin and Snaydon 1982, Ofori and Stern 1987). Although polyculture yield advantages are more common under conditions of low soil nitrogen availability (Hiebsch and McCollum 1987), they are not necessarily eliminated by increases in nitrogen fertility. Large polyculture yield advantages have been obtained when nitrogen fertilizer has been applied at rates considered adequate to fully satisfy polyculture demand (Osiru and Willey 1972, Willey and Osiru 1972).

Interspecific facilitation occurs when crop species grown in polycultures have access to resources not available in monocultures or when they enjoy
improvements in microhabitat that result in greater resource conversion efficiencies (Vandermeer 1989). If one of the component species in a polyculture is a legume bearing nitrogen-fixing bacteria on its roots, atmospheric nitrogen may be transferred to associated non-legumes and increase their yield considerably (Ofori and Stern 1987). Agboola and Fayemi (1972) observed this phenomenon with maize/mung bean mixtures, as did Kapoor and Ramakrishnan (1975) with wheat/Trigonella polycerata mixtures and Eaglesham et al. (1981) with maize/cowpea mixtures. Increased water use efficiency (assessed as CO₂ gained through photosynthesis/H₂O lost as transpiration) has been noted for low-growing crops grown in the shelter of taller crops acting as windbreaks (Radke and Hagstrom 1976).

Interspecific facilitation is an important feature of certain alley cropping systems, in which annual crops are sown in strips between rows of woody perennials; the perennial vegetation is typically pruned for use as mulch, forage, building materials, or firewood. Use of Gliricidia sepium, a leguminous tree species, as a source of mulch and a living support system for vining water yams was found to increase yam yields more than twofold in Nigeria (Budelman 1990a, 1990b). Palada et al. (1992) reported increases in crop nutrient status and yield of four vegetable crops (Amaranthus cruentus, Celosia argentea, okra, and tomato) that were alley cropped with Leucaena leucocephala, another leguminous tree species; the Leucaena hedgerows were used as a source of mulch. Annual crops grown in association with trees may benefit when leaves of the deeper-rooted perennials fall and decompose, releasing nutrients, as with millet planted beneath Acacia albida trees (Charreau and Vidal 1965).

Changes in resource partitioning may occur in polycultures, such that greater percentages of total dry matter and nutrients are allocated to harvestable portions of crops when they are grown in mixture than when grown separately (Willey 1990). Where this occurs, each unit of materials acquired through photosynthesis or root uptake produces a greater benefit for the farmer in polycultures than monocultures. For example, Natarajan and Willey (1981) observed that seeds constituted 19 percent of pigeon pea's total above-ground weight when this crop was grown in monoculture, but 32 percent of its total above-ground weight when it grew in mixture with sorghum. The increased allocation of carbon and nutrients to seeds meant that seed yield of the intercropped pigeon pea plants was quite high, even when their overall size was greatly reduced by their association with sorghum. Of particular interest are the results of Natarajan and Willey (1986). These researchers found that increases in allocation ratios for sorghum, millet, and groundnut that occurred when they grew in polycultures were most marked under drought conditions. The polycultures were most advantageous for seed yield when water availability most severely affected overall plant productivity.
Effects of Polycultures on Insect Pests

Insect pests are frequently less abundant in polycultures than in monocultures. Andow (1991a) reviewed 209 published field studies on 287 herbivorous arthropod species and found that 52 percent of the pest species in the survey were less abundant in polycultures, 15 percent were more abundant in polycultures, 13 percent showed no difference and 20 percent showed a variable response. The same review noted that 53 percent of the predator and parasitoid species that act as natural enemies of insect pests were more abundant in polycultures than monocultures; 9 percent of the natural enemy species were less abundant, 13 percent showed no difference, and 26 percent showed a variable response in polycultures. Thus, use of polyculture production systems may increase the importance of predators and parasitoids as natural controls of populations of insect pests. Root (1973) termed this explanation for lower populations of insect pests in polycultures the enemies hypothesis.

Why might natural enemies of insect pests be more abundant in polycultures than monocultures? Andow (1991a) describes a number of possible reasons that include increases in the variety and quantity of available food sources, improvements in microhabitat, changes in chemical cues affecting location of insect pest species, and increases in the stability of predator-prey and parasitoid-host population dynamics (Chapter 13). These factors may act to improve the survival, reproductive success, and efficiency of natural enemies.

A second explanation advanced for the lower abundance of insect pests in polyculture as compared to monoculture is Root's (1973) resource concentration hypothesis: insect pests, particularly species with a narrow host range, have greater difficulty in locating and remaining upon host plants in small, dispersed patches as compared to large, dense, pure stands. These behavioral changes may result from increased chemical and visual interference with cues used in host plant location or modifications of microhabitat and host plant quality (Andow 1991a). Results of studies supporting the resource concentration hypothesis are described in Chapter 13.

Despite the large number of studies documenting lower abundance of insect pest species in polycultures, relatively few studies have examined whether reduced pest populations are correlated with improved crop productivity. Andow (1991b) reviewed six studies permitting 41 comparisons of pest populations and crop productivity in polycultures and monocultures and concluded that decreases in pest populations in polycultures were often, but not always, correlated with improved crop performance. More research is needed to better understand the ecological mechanisms affecting insect
pest populations and their yield-related impacts in polyculture production systems.

**Effects of Polycultures on Plant Pathogens**

Little research has yet been done on the ecology and management of plant pathogens in polycultures (Sumner et al. 1981). In some cases the incidence of disease has been shown to be higher for crops grown in polycultures than monocultures; in other cases the reverse situation occurs. For example, in experiments conducted in Costa Rica, Moreno (1975) found that, compared with a monoculture of cassava, the severity of cassava mildew was greater when cassava grew with maize but lower when cassava grew with beans or sweet potato. Moreno (1979) also found that the severity of angular leafspot on beans was greater in association with maize but lower in association with cassava or sweet potato, compared with a monoculture of beans.

Researchers are just beginning to understand the underlying mechanisms that affect diseases in different cropping systems. The following aspects of polycultures may be important for improving plant health:

1. Susceptible plant species can be planted at lower densities in polycultures than monocultures since the space between them can be occupied by resistant plant species that are valuable to the farmer. Decreased density of susceptible plants can decrease the spread of diseases by reducing the amount of tissue that is infected and subsequently serves as a new source of inoculum. For some diseases, increasing the distance between susceptible plants by reducing their density can also reduce the spread of inoculum. This was noted for monocultures and mixtures of barley and wheat exposed to barley mildew (Burdon and Whitbread 1979).

2. Resistant plants interspersed among susceptible plants can intercept disease inoculum spread by wind or water and prevent it from infecting the susceptible plants (the "flypaper effect"). Moreno (1979) suggested this as the mechanism for the decreased incidence of *Ascochyta phaseolorum* on cowpea when this crop was sown in association with maize.

3. The microclimate of polycultures may be less favorable for disease development. Reduced severity of several pea diseases has been observed when pea vines climb up associated cereals, rather than lying matted on the ground (Johnston et al. 1978). Intercropping the peas with the cereals improves air circulation and reduces humidity. In other crop mixtures, denser canopy coverage may increase humidity and reduce light penetration, favoring certain fungal and bacterial diseases (Palti 1981). The latter effect may require the use of spatial arrangements in polycultures that promote a more open canopy configuration.

4. Excretions from or microbes on the roots of one crop species may affect soil disease organisms that attack roots of an associated crop species. This
appears to be the mechanism responsible for the decreased incidence of *Fusarium udum* wilt of pigeon pea when this crop grew in polycultures with sorghum (ICRISAT 1984).

Very little research has focused on the effects of polycultures on pest nematodes. However, it has been well established that nematodes prefer particular crop species (Palti 1981) and that certain plants, such as marigolds (*Tagetes* spp.), excrete substances that are toxic to nematodes (Cook and Baker 1983). These effects suggest it may be possible to decoy, trap or kill nematodes by interplanting certain crop species amid other crops that require protection. Visser and Vythilingam (1959) reported that marigolds growing between tea bushes reduced populations of nematodes in the soil and in tea roots. When the legume cover crop *Crotalaria spectabilis* was sown in peach orchards, nematodes attacked the legume rather than the tree crop, increasing fruit yields (Cook and Baker 1983). Additional examples of the effects of polycultures on pathogenic bacteria, fungi, viruses, and nematodes are described in Chapter 13.

In a situation analogous to that concerning pest insects in polycultures, little is known concerning the yield-related impacts of pathogens in polycultures. Burdon (1987) noted that without appropriate experimental designs, it is impossible to tell whether improved resource use efficiency or decreased incidence of disease symptoms is responsible for higher yields in polycultures. More research concerning the ecology and management of pathogens in polycultures is needed.

*Effects of Polycultures on Weeds*

Weed control is one of the most labor-intensive aspects of tropical agriculture and one of the most chemical-intensive aspects of temperate agriculture. As compared to monoculture cropping systems, polycultures appear to offer many options for improving weed control with less labor, fewer chemicals, and lower costs.

A review of the polyculture/weed literature conducted by Liebman and Dyck (1993) compared weed growth in polycultures to that in monocultures of the component crops. Two types of polyculture systems were examined: systems in which the farmer is interested primarily in the yield of a main crop species and intersows a smother crop for weed control, erosion control, improved soil fertility, and a small amount of additional crop yield; and systems in which the farmer is interested in yield of all the component species, none of which is sown specifically for weed control. In the former situation, weed growth in polyculture was lower in 47 cases and higher in four cases than the main crop grown alone. In the latter situation, weed growth in polyculture was lower than in all of the component monocultures
in 12 cases, intermediate between component monocultures in 10 cases, and higher than monocultures of all components in two cases.

A considerable amount of research has documented the utility of polycultures for weed control in Nigerian cropping systems. Akobundu (1980) reported that in terms of crop yields and weed suppression, smother crops of egusi melon and sweet potato could replace three hand weedings when they were sown into sole-cropped yam, sole-cropped maize and polyculture combinations of yams, maize, and cassava. The vining smother crops not only served as a labor-saving means of weed control, but also provided erosion control through increased soil coverage. Zuofa et al. (1992) found that intercropping smother crops of groundnut, cowpea, or melon with a cassava/maize main crop gave superior weed control, highest total yields, and highest land equivalent ratios. Maize intercropped with smother crops of sweet potato, cowpea, groundnut, or melon plus one hand weeding was found to provide higher net income than monoculture maize hand weeded three times or sprayed with herbicides (Zuofa and Tariah 1992). Obiefuna (1989) reported that planting melons between plantains reduced weed growth such that weeding could be delayed for up to seven months after planting.

In experiments conducted in India, Shetty and Rao (1981) found that adding smother crops of cowpea or mung bean to main crops of sorghum or pigeon pea resulted in less early season weed growth and decreased the number of hand weedings necessary for high crop yields from two to one. The smother crops had no effect on yield of the main crop species and provided additional yield themselves. Abraham and Singh (1984) measured the crop yield and weed suppression effects of adding cowpea, groundnut, soybean or mung bean to sorghum. Intersowing any of the four annual legumes increased yield and nitrogen content of sorghum and depressed weed growth below levels in sole-cropped sorghum. Forage or seed yield of the legumes was an additional benefit. Similar results were obtained by Tripathi and Singh (1983) when they added soybean to maize. Sengupta et al. (1985) demonstrated that interseeding blackgram into rice (21 days after planting rice) effectively suppressed weed growth, eliminated the need for one hand weeding, and increased total crop yield and income, as compared to monoculture rice. Ali (1988) reported that total seed yields of pigeon pea/mung bean intercrops without any hand weeding were very close to yield levels obtained from weeded, monoculture pigeon pea. Weed growth in the polyculture was 22–38 percent lower than in unweeded, monoculture pigeon pea; added yield from the mungbean smother crop compensated for the loss of pigeon pea yield due to weed competition.

In temperate climates, interseeding green manure legumes into cereal and grain legume crops can provide increased weed control for the main crops, furnish ground cover for erosion control during the autumn and winter, and
improve soil fertility. Harwood (1984) reported that in Pennsylvania, interseeding red clover or hairy vetch into maize or soybeans (planted 35 days earlier and cultivated once) had no effect on yields of the concurrent grain crops, greatly reduced weed growth, created nearly complete soil cover, and reduced nitrogen fertilizer requirements for subsequent crops. In experiments conducted in Britain, adding Italian ryegrass or red clover to barley or faba beans was found to decrease growth of the perennial grass weed *Agropyron repens*, growing from either seeds (Williams 1972) or rhizomefragments (Dyke and Barnard 1976). In New Jersey, maize planted without tillage and without herbicides into established subterranean clover produced as much or more biomass and grain as monoculture maize grown with herbicides, either with or without tillage (Enache and Ilnicki 1990). Subterranean clover behaved as a winter annual, growing primarily during spring and autumn months, and lying as a dead mulch between maize rows during the summer. In Texas, interseeding subterranean clover or arrowleaf clover into pastures of Bermuda grass or Bahia grass essentially eliminated weeds from the pastures; interseeding provided weed control as good or better than that obtained with herbicide application (Evers 1983).

Many polycultures exploit a greater proportion of available light, nutrient, and water resources than monocultures, therefore, some researchers have suggested that polycultures may suppress the growth of weeds more effectively than monocultures through greater preemptive use of resources. However, examination of available data concerning resource use patterns, and weed and crop productivity in polycultures shows that the resource preemption hypothesis may be true in some cases but not others (Liebman and Dyck 1993). Understanding the resource-related mechanisms of polyculture/weed interactions will require considerably more research involving measurements of resource availability and resource capture by crops and weeds throughout the growing season.

Crop density, choice of crop species and cultivar, crop spatial arrangement, and fertilizer regime have all been shown to affect polyculture/weed interactions (Moody and Shetty 1981, Liebman 1988, Liebman and Dyck 1993). In general, increases in crop density result in increased suppression of weed growth (examples: Shetty and Rao 1981, Mohler and Liebman 1987). Polycultures that include species and cultivars with rapid, early growth and dense, vigorous canopy formation over the ground surface are particularly effective in reducing weed growth (Bantilan et al. 1974, Abraham and Singh 1984, Liebman 1989, Samson et al. 1990).

The effects of different crop spatial arrangements and fertilizer regimes appear to be more variable. For example, Prasad et al. (1985) reported less weed growth in pigeon pea/sorghum polycultures when pigeon pea was sown in paired rather than evenly spaced rows; in contrast, Ali (1988) found that polycultures of urd bean, mung bean, soybean, cowpea, or sorghum with
pigeon pea planted in a uniform row arrangement suppressed weed growth more effectively than polycultures with pigeon pea planted in paired rows. Bantilan et al. (1974) observed that nitrogen fertilizer increased competitive suppression of weeds by maize/mung bean polycultures, but it either decreased or had no effect on weed suppression by maize/groundnut and maize/sweet potato polycultures. The variability of these results indicates that before generalizations or predictions can be made regarding the effects of crop spatial arrangements, fertilizer regimes, and other factors on polyculture/weed interactions, the ecophysiological mechanisms that drive these interactions need to be better understood.

**Future Directions**

Increasing vegetational diversity through use of polycultures is not a panacea for problems with crop production and protection, but it can offer farmers potentially useful options for decreasing dependence on purchased external inputs, minimizing exposure to agrichemicals, reducing economic risk and nutritional vulnerability, and protecting the natural resource base necessary for agricultural sustainability. The task for the future is to better understand the dynamics and complexities of polycultures so that these systems may be refined, transferred, and adapted, and so that benefits can be gained predictably. Vandermeer (1989) has indicated many areas where application of ecological theory may greatly aid the design and management of polyculture systems.

The prevalence of polycultures in developing countries suggests that many farmers there are well aware of the benefits of these systems. It seems extremely counterproductive to try to convince farmers to abandon the use of polycultures where and when benefits can be obtained. Instead, researchers working in developing countries should develop crop varieties and management practices (e.g., determination of optimum spatial arrangements, densities, etc.) that are compatible with and improve the performance of polyculture systems (Francis et al. 1976; Krantz 1981). One example of an appropriate technology for polycultures is the design and production of low-cost, animal-drawn planters and cultivators specifically for crop mixtures (Anderson 1981). Pest control and soil fertility aspects of polyculture systems deserve much more attention in developing countries where access to synthetic pesticides and fertilizers is limited by socioeconomic conditions and considerations of human and environmental health.

The role of polycultures in the agriculture of developed countries will probably expand as there is increased perception of the economic and environmental costs of heavy reliance on agricultural chemicals (Horwith 1985). Although agriculture in these countries is extensively mechanized, polyculture systems can be compatible with mechanization (e.g., green
manure legumes interseeded into grains; soybeans relay-cropped with wheat; cover crops for orchard floors). As in the developing countries, crop varieties and management practices are needed that will enhance the benefits of existing polyculture systems. Increased attention to the design of machines for other types of crop mixtures might allow the potential biological benefits of these systems to reach farmers in a practical way. As Cordero and McCollum (1979) noted, any society that can land people on the moon and retrieve them safely should be able to design machinery to plant, maintain, and harvest polycultures.
Cover Cropping and Mulching

Cover cropping is the practice of growing pure or mixed stands of annual or perennial herbaceous plants to cover the soil of croplands for part or all of the year. The plants may be incorporated into the soil by tillage, as in seasonal cover cropping, or they may be retained for one or several seasons. When plants are incorporated into the soil by tillage, the organic matter added to the soil is called green manure.

Benefits of Cover Cropping in Orchards

Cover crops are legumes, cereals, or an appropriate mixture grown specifically to protect the soil against erosion; ameliorate soil structure; enhance soil fertility and suppress pests, including weeds, insects, and pathogens. Figure 10.1 outlines some principal benefits of cover crops. Cover crops are not grown for harvest, but rather to fill gaps in either time or space when cash crops would leave the ground bare. Most cover crops are grown during the cold season in northern latitudes and during the dry season in tropical climates. In northern latitudes, rye (Secale cereale L.), clover (Trifolium spp.), or vetch (Vicia spp.) are planted in the fall to specifically provide a winter cover. In addition, alfalfa (Medicago sativa) is also left in the field during winter months. In tropical climates, legumes, such as Pueraria, Stylosanthes, and Centrosema, and grasses, including Brachiaria, Melinis, and Panicum, are grown in the short, rainy season and left in the field throughout the dry season (Lal et al. 1991).

The possible benefits of cover cropping in orchards and vineyards include (Finch and Sharp 1976, Haynes 1980):

1. Improves soil structure and water penetration because adding organic matter and roots increases soil aeration and the percentage of water-stable
aggregates. Tillage requirements and equipment travel are decreased, thereby reducing soil compaction and tillage pan. Vegetative cover can better support machinery during wet periods. The cover crop intercepts water drops, reducing their force and preventing crust formation.

2. Prevents soil erosion by spreading and slowing the movement of surface water, reducing runoff and holding the soil in place with root systems.

3. Improves soil fertility by adding organic material to the soil during decomposition and by making nutrients in the soil more available through nitrogen fixation.

4. Controls dust by holding the soil in place with root systems.

5. Aids in controlling insect pests by harboring beneficial insect predators and parasites.

6. Modifies the microclimate and temperature by reducing reflection of sunlight and heat and increasing humidity in the summer.

7. Minimizes competition between the main crop and noxious weeds.

8. Reduces soil temperatures.

In Europe, Boller (1992) considers the establishment of a permanent or temporal cover crop a key management practice to transform monoculture vineyards into agroecosystems of increasing ecological diversity and stability.

FIGURE 10.1 Potential benefits of cover crops (Lal et al. 1991).
This flora functions as a major ecological "turntable" which activates and influences key processes and components of the vineyard agroecosystem: the complex of beneficial fauna, soil biology, and nitrogen cycle (Figure 10.2).

**Effects on Soil Fertility**

The value of cover crops in maintaining soil fertility in orchards depends partly on the production of reasonably heavy tonnages of organic matter. Purple vetch can produce 20 tons of green manure per acre, whereas other legumes produce from 12 to 13 tons per acre. Purple vetch and sweet clover can produce net gains of nitrogen of up to 150 pounds/acre/year.

Four different cover management systems were widely tested in Malaysia's rubber tree (*Hevea*) plantations, a mixture of creeping legumes (*Calopogonium mucunoides*, *Centrosema pubescens*, and *Pueraria phaseoloides*), grasses (mostly *Axonopus compressus* with *Paspalum conjugatum*), a pure crop of *Mikania cordata*, and a naturally regenerating system representing the normal colonization process on cleared land.

Of the four systems, legumes initially had the fastest rate of growth, and generally contained more nutrients than the other covers tested. The greater nutrient return to the soil from a leguminous cover was reflected in higher levels of these nutrients in rubber leaves. Coupled with improved soil physical properties, this led to an increased rate of growth of the rubber tree. Nitrogen fixation under legumes grown in association with rubber averaged 150 kilograms per hectare per year over a five-year period. Maximum rates of nitrogen fixation were about 200 kilograms per hectare per year.

Two hypotheses may explain these effects. First, that legumes recycle nutrients at or near the soil surface until they can be efficiently used by *Hevea*.

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**FIGURE 10.2** The four important turntables of a diversified vineyard as influenced by a green cover crop (after Boller 1992).
and second, that legumes, by processes not fully understood, cause increased proliferation of Hevea roots, which facilitates nutrient uptake (Broughton 1977).

Plants that are useful under some conditions may be a liability under others. Cover crops used in orchards and vineyards may compete with trees or vines for water and nutrients, and certain weeds may proliferate, reducing the cover crop stand substantially. In areas where it is impractical to grow legumes, it may be advisable to turn to mustards, malva, and rapeseed. These plants contain large percentages of nitrogen and quickly decompose if turned under before reaching maturity. Mustards grow very rapidly and can choke out other undesirable weeds. Cover crop plant residues may also interfere with harvesting of fruits and nuts.

Effects on Insect Populations

Soviet researchers found that the effectiveness of the parasitic wasp Aphytis proclia in controlling the San Jose scale improved as a result of planting a Phacelia tanacetifolia cover crop in the orchards. Three successive plantings of the Phacelia cover crop increased parasitization of scales from 5 percent in clean cultivated orchards to 75 percent where honey producing plants were grown and in full bloom (Altieri and Whitcomb 1979).

In northern California, manipulation of ground cover vegetation in apple orchards and vineyards had a substantial impact on the abundance of soil-dwelling and foliage-inhabiting arthropods. Systems with cover crops were generally characterized by lower densities of phytophagous insects, less fruit damage caused by insects on the trees, larger populations, and more species of natural enemies and increased predation of artificial prey. Cover crops that remained in full bloom throughout the season, that produced more biomass and supported higher numbers of alternative prey, seemed to harbor the largest complex of predators and parasites.

In California, the beetle Hippodamia convergens is the most important predator of walnut aphid (Chromaphis juglandicola) during the early season. This beetle moves from its overwintering area in the mountains to the walnut (Juglans spp.) orchards in February and early March, when there are no leaves on the trees and therefore no aphids. However, some aphids are present in the ground cover under the trees, and serve as a temporary food source for the predators, which would otherwise move on or die of starvation. The ground cover under the trees should be chopped or disked in late April or early May to force the beetles onto the walnut trees. If it is chopped too early, however, the beetles will emigrate before the walnut aphids have appeared on the trees and if it is chopped too late, the large number of beetles will decimate the aphid population on the trees without ovipositing, resulting in fewer beetles later. Thus, timing of the chopping of
the ground cover is critical to maintain ample beetle population for sufficient
control of the aphids (Sluss 1967).

In California's Central Valley vineyards, variegated leafhopper population
differences between cover and noncover plots were clearly different for all
three broods, but the reasons behind these differences were not so clear.
Anecdotal reports from growers in the area suggest that weedy cover crops
in early to mid-season may have smaller populations of leafhoppers. An
increase in the abundance of generalist predators, especially spiders, may
help reduce leafhopper populations in the weed-cover plots (Settle et al.,
1986). In the same area, leaving a managed ground cover of Johnson or
Sudan grass, a minor cultural practice modification in vineyards, resulted in
a habitat modification which greatly enhanced the activity of predators
against phytophagous mites such as the Willamette mite, Eotetranychus willa-
mette. When Johnson grass (Sorghum haepense) was allowed to grow in grape
vineyards, there was a buildup of alternate prey mites, which supported
populations of the predatory mite Metaseiulus occidentalis, which, in turn,
restrained the Pacific mite, Tetranychus pacificus to noneconomic numbers
(Flaherty 1969).

Also in the San Joaquin Valley, the emergence of navel orangeworm adults
(Amyeolis transitella) was significantly higher in the residual herbicide-treated
almond orchard than in orchards with a vegetation cover. These results show
that fewer navel orangeworms survive the winter on the ground when cover
crops are present. The differences might be greater where nuts with cover crops
are fully subjected to regular, early spring mowing. Nuts with residual herbicide
treatments, which do not need mowing, would not be disturbed.

Apparently, cover crop manipulation can directly affect colonization of
insect pests that discriminate among trees with and without cover beneath,
and can also help retain populations of natural enemies that inhabit soil and
foliage by providing alternative food and habitat. The design of proper
cover crop/orchard mixtures can enhance biological control of specific pests
in existing orchards and vineyards (Altieri and Schmidt 1985).

Types of Cover Crop Management

The drawbacks of cover crop systems can be reduced or eliminated with
careful management and agronomic practices. Limitations are small
compared with the alternatives. The most common cover crop management
systems are (Finch and Sharp 1976):

Nontillage Systems. Under a nontillage management system the cover crop
is mowed rather than disked into the ground. Nontillage reduces soil
compaction and soil erosion and improves water infiltration. A nontillage
system can be started in an existing or new orchard. An existing orchard
should be properly prepared soon after harvest. It is particularly important
to do a good job of leveling and grading, since the soil will not be reworked. For initial planting of a cover crop, Table 10.1 provides recommended seed-age/acre and methods of sowing for different species proper for California.

**Frequent Clipping.** In this system the cover crop is clipped four to seven times, beginning in early spring. This system is used with drag-hose operations and with sprinkler, border, furrow, and drip irrigation systems. Frequent mowing eliminates the use of many deep-rooted, reseeding annual and perennial plants. Low-growing, reseeding annuals or perennials do best under this type of management.

**Infrequent Clipping.** In this system the cover crop is infrequently clipped, usually in early spring for frost protection and in late spring for residue control. It is not well-adapted to drag-hose irrigation. This system permits the use of deep-rooted, reseeding annual or perennial plants. If reseeding annuals are used, spring mowing must be timed to allow a crop of seed to mature for the next year's stand. Through close and careful management the danger from frost or residue buildup can be minimized.

**Tillage Systems.** Under a tillage system, the cover crop is disked into the soil after the seeds have matured. For optimal timing for various species see Table 10.1.

**Annually Fall-Seeded Cover Crop.** In this system fall-seeded cover crops are disked into the soil in early spring, followed by either summer fallow until fall, or volunteer summer annuals. Early tillage is used to turn under the green manure crop and reduce danger of frost damage. This system can be used with all types of irrigation in most orchards and vineyards. Frequent tillage is a disadvantage because only short-season annual plants can be used, and the soil is exposed for much of the year.

**Reseeding Winter Annual Cover Crop.** Reseeding winter annuals are disked under in late spring, followed by either summer fallow until fall, or volunteer summer annuals, which are mowed, then disked under in the fall. The cover crop can be clipped until late spring to control vegetation height. Mowing must be timed to allow the reseeding annuals to produce a mature seed crop before disking. Many reseeding, deep rooted annuals are ideal for this system.

**No Winter Cover.** In this system winter cover is eliminated by cultivation or chemical control. This is followed by either volunteer summer annuals, annually summer-seeded annuals, or reseeding summer annuals. The summer cover is used from mid-spring until frost. This system works well with border, furrow, or sprinkler irrigation. It is most frequently used in table grape vineyards and has possible use in citrus.

In some citrus-growing areas, particularly in Florida, cover crops are useful in summer because it is the season of greatest rainfall. In other areas, such as California, the heavy rains come in winter, which may be the only season when it is practical to grow a cover crop. In the large irrigated areas of
### TABLE 10.1 Partial list of species and some management characteristics of cover crop plants recommended for California orchards and vineyards (after Finch and Sharp 1976).

<table>
<thead>
<tr>
<th>Cover cropping species¹</th>
<th>Planting density (seed lb/acre)</th>
<th>Management system</th>
<th>Disked/Mowed</th>
<th>Special features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley (Hordeum vulgare)</td>
<td>90</td>
<td>Tillage</td>
<td>Spring</td>
<td>Fast grow. winter</td>
</tr>
<tr>
<td>Cereal rye (Secale cereale)</td>
<td>60</td>
<td>Tillage</td>
<td>Spring</td>
<td>Fast grow. winter</td>
</tr>
<tr>
<td>Annual ryegrass (Lolium multiflorum)</td>
<td>9</td>
<td>Tillage</td>
<td>Spring</td>
<td>Late matur. winter annual</td>
</tr>
<tr>
<td>Purple vetch (Vicia atropurpurea)</td>
<td>52</td>
<td>Tillage</td>
<td>Spring</td>
<td>N fixer</td>
</tr>
<tr>
<td>Blando brome (Bromus mallis)</td>
<td>6</td>
<td>No till</td>
<td>Spring²</td>
<td>Good reseed ability</td>
</tr>
<tr>
<td>Cucamonga brome (Bromus mallis)</td>
<td>12</td>
<td>No till</td>
<td>Spring²</td>
<td>Mature April</td>
</tr>
<tr>
<td>Wimmera 62 ryegrass (Lolium rigidum)</td>
<td>9</td>
<td>No till</td>
<td>Spring²</td>
<td>Well adapted lowland</td>
</tr>
<tr>
<td>Annual bluegrass (Poa annua)</td>
<td>5</td>
<td>No till</td>
<td>Freq. mowing</td>
<td>Mature early April</td>
</tr>
<tr>
<td>Lana vetch (Vicia dasycarpa)</td>
<td>15</td>
<td>No till</td>
<td>Infreq. mowing</td>
<td>Reseeds well</td>
</tr>
<tr>
<td>Rose clover (Trifolium hirtum)</td>
<td>9</td>
<td>No till</td>
<td>Spring²</td>
<td>Early matur., poor competitor</td>
</tr>
<tr>
<td>Crimson clover (T. incarnatum)</td>
<td>9</td>
<td>No till</td>
<td>Freq. mowing</td>
<td>Adapt. acid soils</td>
</tr>
<tr>
<td>Bur clover (Medicago hispida)</td>
<td>9</td>
<td>No till</td>
<td>Freq. mowing</td>
<td>Reseeds well</td>
</tr>
<tr>
<td>Black medic (Medicago sp.)</td>
<td>6</td>
<td>No till</td>
<td>Freq. mowing</td>
<td>Adapt. alkaline soils</td>
</tr>
</tbody>
</table>

¹ All cover crops are planted in California.
² Proper for frequent mowing but must be allowed a regrowth of 3–4 weeks prior to seed maturity.
California, the water supply is insufficient to grow a cover crop in summer and also provide for tree moisture requirements. A cover crop of 10 tons per acre may require 12 inches or more of water per acre.

**Disposal of Cover Crop.** For a cover crop to be beneficial, it must decay in the orchard or vineyard. To promote decomposition, the material must be incorporated with damp soil. Therefore, it is advisable to turn under a cover crop deeper than that provided by shallow summer cultivation. Care should be exercised, however, to make sure that plowing and disk ing is not so deep as to cut many tree roots. All orchard disks should be equipped with rollers to prevent excessive penetration. It is sometimes desirable to break down a large cover crop with a drag or disk before working the crop into the soil. This procedure makes plowing or final disk ing easier, and lessens the loss of water by transpiration, a result to be desired if the soil is drying out faster than the cover crop can be turned under.

**Cover Crop Plants.** A good cover crop plant maintains or improves soil conditions while it satisfies the soil, site, and management requirements of a particular orchard or vineyard. The wide variety of management systems in orchards and vineyards creates demand for a diversity of cover crops. Grasses have fibrous root systems that make them particularly useful in building soil structure, providing erosion control, and improving water penetration. Legumes are not as effective as grasses in improving water penetration but they do contribute nitrogen to the soil and their residues break down more rapidly. Plants useful as cover crops can be classed as annually seeded winter-growing grasses and legumes, reseeding winter annual grasses and legumes, summer annuals, perennial grasses and legumes, and other cover crop plants.

**Living Mulches**

Using legume cover crops in year-round cropping systems and rotations offers a great potential for sustained crop production and self-sufficiency in soil nutrients. Legume cover crops used in association with annual crops are generally called living mulches. Most research on these systems has been conducted on corn, soybeans, and vegetable crops in the form of legume overseeding, sod rotation, and sod interplanting (Miller and Bell 1982).

Legume species commonly used as living mulches include short white clover, hairy vetch, and red clover. Growth characteristics of representative legumes usually used as living mulches are presented in Table 10.2. Except for alfalfa, most legume species are annuals or biennials. Adaptations range from semi-temperate for hairy vetch, and crimson clover to temperate for alfalfa, winter pea, and sweet clover. Dry matter production ranges from 2.3 tons per hectare for sweet clover to 10 tons per hectare for alfalfa and hairy vetch. Based on tissue nitrogen content and dry matter production, these legumes...
TABLE 10.2 Growth characteristics of legume species used as cover crops (after Palada et al. 1983).

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Scientific Name</th>
<th>Growth habit</th>
<th>Adaptation</th>
<th>Dry matter (t/ha)</th>
<th>Total N (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td><em>Medicago sativa</em></td>
<td>P</td>
<td>temperate</td>
<td>10.0</td>
<td>170</td>
</tr>
<tr>
<td>Crimson clover</td>
<td><em>Trifolium incarnatum</em></td>
<td>A</td>
<td>semi-temperate</td>
<td>7.9</td>
<td>179</td>
</tr>
<tr>
<td>Hairy vetch</td>
<td><em>Vicia villosa</em></td>
<td>A</td>
<td>semi-temperate</td>
<td>10.2</td>
<td>376</td>
</tr>
<tr>
<td>Medium red clover</td>
<td><em>T. pratense</em></td>
<td>B, P</td>
<td>semi-temperate</td>
<td>5.2</td>
<td>146</td>
</tr>
<tr>
<td>Short white clover</td>
<td><em>T. repens</em></td>
<td>B</td>
<td>semi-temperate</td>
<td>5.2</td>
<td>182</td>
</tr>
<tr>
<td>Yellow sweet clover</td>
<td><em>Melilotus officinalis</em></td>
<td>B</td>
<td>temperate</td>
<td>2.3</td>
<td>76</td>
</tr>
<tr>
<td>Winter pea</td>
<td><em>Pisum sativum</em></td>
<td>A</td>
<td>temperate</td>
<td>6.0</td>
<td>213</td>
</tr>
</tbody>
</table>

* A = annual, B = biennial, P = perennial

fix from 76 to 367 kg of nitrogen per hectare. This is sufficient to meet most of the nitrogen requirements, of agronomic and vegetable crops (Palada et al. 1983).

Most legume cover crops do not tolerate acid or dry soil but do tolerate shade and field traffic, which are ideal characteristics for intercropping. Resistance to severe winter frost is important if the legumes are to be grown for soil nitrogen. Winter survival and spring regrowth seem to be fair with selected species.

Cropping Systems with Legume Cover Crops

Legume cover crops can be incorporated into year-round cropping systems by overseeding (interseeding), legume sod-based rotations, sod strip intercropping, or vegetable living-mulch systems (Palada et al. 1983).

Legume Overseeding

Overseeding legume cover crops into small grains in the spring has been a standard farming practice for several decades. It is a low-cost, efficient
way to establish the sod rotation. Midwest farmers overseed legume cover crops when planting corn, soybean, or vegetable crops or before harvesting to maintain soil fertility.

In 1980, researchers at the Rodale Research Center examined the effects of legume species, time of overseeding, and plant population on corn and soybean yields (Palada et al. 1983). Legumes overseeded during the first cultivation of the crop cycle had better germination and higher seedling emergence than those overseeded during the second cultivation. Overseeding during the first cultivation also provided significantly better ground cover than the second overseeding. These results suggest that during a dry summer, early overseeding provides excellent fall and winter ground cover. Legume cover crops did not reduce grain yield of corn and soybean (Table 10.3). Weed competition in both crops was also significantly reduced by overseeding.

Light level has a major influence on the survival and persistence of legume cover crops under row crop canopies. As the soybean canopy begins to close, the light intensity under the canopy decreases, suppressing sod growth. At full canopy, the sod is eliminated because light penetration under soybeans is low. Researchers at Rodale Research Center are trying to identify species that will fix nitrogen and control erosion through fall, winter, and early spring. This legume cover crop could either be plowed down in the early spring before planting another summer crop, or it could be continued as a sod rotation into the next year. Legume species that appear to have real promise are red and white clover, Austrian winter pea, and hairy vetch.


<table>
<thead>
<tr>
<th>Time of Overseeding</th>
<th>Legume Species</th>
<th>Grain Yield (t/ha)</th>
<th>Weed Reduction*</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 DAP^b</td>
<td>Medium red clover</td>
<td>7.30</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Hairy vetch</td>
<td>7.13</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Control (no overseeding)</td>
<td>7.49</td>
<td>--</td>
</tr>
<tr>
<td>47 DAP^c</td>
<td>Medium red clover</td>
<td>6.96</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>hairy vetch</td>
<td>7.35</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Control (no overseeding)</td>
<td>7.13</td>
<td>--</td>
</tr>
</tbody>
</table>

* The legume overseeding resulted in an average of 95% ground cover for both species.

^b DAP = days after planting corn, one cultivation prior to overseeding.

^c DAP = days after planting corn, two cultivations prior to overseeding.
**Legume Sod-Based Rotations**

Legumes in rotation or as green manure are useful in controlling soil erosion and maintaining soil organic matter. A typical three- to six-year crop rotation common among organic farmers in the Midwest and Northeast states involves alfalfa or clover, corn, soybeans, and small grains, with the number of years of alfalfa or clover increasing with increasing slope.

Well-inoculated legumes provide substantial nitrogen for the next planting of grain crops. For example, first year alfalfa yielding seven to 11 tons per hectare will furnish most of the nitrogen needs of a following corn crop with corn yield equal to or higher than that of continuous corn fertilized at 150 to 200 kg of nitrogen per hectare. A nitrogen fertility trial in corn conducted in 1979/1980 at the Rodale Research Center showed no yield response to added fertilized nitrogen in fields that were organically managed and rotated with legume cover crops for more than five years. Legume/grass mixtures and clovers in which legumes are dominant are as effective in fixing nitrogen as a pure alfalfa stand producing the same amount of hay. However, alfalfa frequently yields more hay (Palada et al. 1983).

**Sod Strip Intercropping**

In strip intercropping, crops are grown simultaneously in different strips wide enough to permit independent cultivation, but narrow enough for two or more different crops to interact agronomically. The components can be a combination of row crops or a mixture of row crops and legume or grass sod. Using a legume sod is more advantageous from the standpoint of soil nitrogen. Sod strip intercropping may be limited to row crop production in sloping or hillside farms. These systems break the flow of water down the slope, reducing erosion substantially.

In 1978, researchers at the Rodale Research Center studied strip intercropping systems of red clover and short white clover with corn and soybean. Corn was planted in one-meter tilled strips at 40,000 plants per hectare using double rows. Soybeans were seeded in one-meter tilled strips at 250,000 plants per hectare. The check plots consisted of single rows planted in completely tilled soil, with no sod between the rows. Results showed that strip intercropping reduced corn yield by 17 percent to 34 percent, but did not affect soybean yield. Corn intercropped with short white clover had a slightly higher yield than with medium red clover. The researchers concluded that the choice of sod species may depend on how the legume is used other than as a cover crop. Red clover usually provides more biomass than short white clover, so it may be suitable for farmers who would make use of it for hay, silage, or green mulch (Palada et al. 1983).
In another study on the effect of tillage width on corn, the researchers found that the highest yield (7.2 tons per hectare) was obtained from monoculture plots with single rows. Using a 0.75- or 1.5-meter tilled strip produced yields that were higher than other tillage widths. Yield reductions from these plots were only 8 percent and 16 percent, compared with 20 percent to more than 50 percent for other treatments. Rodale researchers concluded that monoculture corn produced more total dry matter than any of the combinations because of its superiority in yield. Although the intercrop system produced less total dry matter, the overall advantage is harvesting two feed crops in addition to reduced soil erosion and increased soil organic matter and nitrogen.

By manipulating tillage width, the system's total productivity can be adjusted to meet the grain and hay requirements of the farm. Tillage width can be adjusted as needed to fit available machinery with no adverse effects on soils and crop yields.

**Vegetable/Living Mulch System**

A living mulch system may be an economical way for vegetable growers to reduce soil erosion, increase organic matter, and keep yields consistent within conventional systems. In 1978, Rodale researchers grew vegetables in existing grass and clover sod. The treatments consisted of red clover sod, bluegrass sod, and completely tilled strips. Planting strips one-half-meter wide at two-meter spacing were prepared using a rotovator. Half of each treatment received 15 cm of alfalfa green chop while the other half was covered with black polyethylene mulch. The mulch was left undisturbed for one week. Sweet corn and tomatoes were planted into the mulched strips. In completely tilled plots, half the rows between planting strips were seeded to short white clover and the other half were kept cultivated throughout the growing season. This was done to determine whether cultivating for weed control had any effect on the crop.

Production data showed that tomatoes grown in sod under a combination of mulch and tillage methods produced more fruit than those grown in a typical clean-cultivated field. Yield of tomatoes was 17 percent higher under alfalfa than under plastic mulch in the grass and clover sod strips, but not in the clean-cultivated field. Plants grown under black plastic mulch wilted and aborted flowers. These factors may have contributed to lower yields under plastic mulch.

The effect of mulch on sweet corn was the opposite of its effect on tomatoes. The most drastic differences occurred between mulch treatments, not between field treatments. More ears were harvested under alfalfa than under plastic mulch. Corn grown under plastic mulch shed pollen about two to four days before silking so that very little pollination occurred and yields declined.
Tilling the planting strips for both corn and tomato did not appear to affect their yields. However, tillage between rows of the clean-cultivated field decreased yields compared with strips seeded to white clover. This study suggests that both sweet corn and tomatoes can be adapted to living mulch systems, provided the living sod is set back by a mulch in the planting strip and enough soil moisture is continuously available. Competition with living sod was not a problem as long as the sod was properly managed.

Effects of Living Mulches on Insect Populations

Although the entomological advantages of living mulch systems are still little understood, experimental work suggests that many of these systems have built-in biological control advantages. Most research has focused on Brassica crops. For example, Dempster and Coaker (1974) found that the maintenance of a clover cover aided in the reduction of three insect pests (Brevicoryne brassicae, Pieris rapae, and Erioischia brassicae). In the case of P. rapae, the reduction was attributable to increased numbers of the predacious ground beetle Harpalus rufipes in the cover-seeded plots. Similar enhancements were observed when planting clover between rows of cabbages, which resulted in a 34% increased predation of eggs of the cabbage root fly, Delia brassicae (Cromartie 1981).

In New York state, an experiment was conducted using cabbage interplanted with several living mulches and in bareground monocultures (Andow et al. 1986). Living mulches used were creeping bentgrass, red fescue, Kentucky bluegrass, and two white clovers. Populations of Phyllotreta cruciferae and Brevicoryne brassicae were lower on cabbage grown with any living mulch than on cabbage in bareground monocultures. First-generation larvae of Pieris rapae were more common on cabbage with clover living mulches, but second-generation eggs and larvae were less common on cabbage with clover living mulches. These differences in population density were probably determined by variation in herbivore colonization rates, not by variation in herbivore mortality. The authors suggest that early season chemical treatments for flea beetles might be eliminated when living mulches are used. However, this potential gain may be offset by yield reduction from competition between cabbage and living mulches.

In two locations in California, Altieri, Wilson, and Schmidt (1985) further tested the effects of vegetation background in the form of living mulches and natural weed cover on the population dynamics of foliage and soil arthropods in corn, tomato, and cauliflower crop systems. In Davis (Central Valley site) herbivores (especially aphids and lygaeids) were more abundant in the plots with weed cover than in the clover mulch plots, whereas leafhoppers were most common in the clover mulch. Higher numbers of natural enemies were observed in the clover plots. Significantly more ground
predators (Carabidae, Staphylinidae, spiders) were caught in pitfalls placed in the weedy and clover plots than in the clean cultivated plots. In Albany (Coastal area), specialized herbivore (cabbage aphids and flea-beetles) densities were significantly reduced in plots with living mulch cover. It is not clear if this reduction was due to plant diversity or density effects, to the effects of natural enemies or to the lower quality of plants in the weedy and mulched plots, as crop growth and yields were drastically reduced in these plots at both sites. In England, undersowing cereals with grass species (e.g., ryegrass) increases the activity of an abundance of natural enemies, including polyphagous predators. This practice appears to be one of the most effective means of enhancing aphid parasitism by *Aphidius* spp. (Burn 1987). A similar effect was shown in Germany where parasitism of *Metopolophium dirhodum* by two parasitoids was higher in wheat undersown with clover than in wheat monoculture (El Titi 1986). Further agronomic work is warranted to minimize the competitive effects of legume covers on crops, so that the observed entomological advantages can be used in a practical way.
Crop Rotation and Minimum Tillage

Crop rotation is a system in which different crops are grown in recurrent succession and in definite sequence on the same land (Page 1972). Several experiments lasting more than 100 years at the Agricultural Experiment Station at Rothamsted, England, and the Morrow plots at the Illinois Agricultural Experiment Station have provided considerable data on the effects of crop rotations. Evidence indicates that crop rotations influence plant production by affecting soil fertility and survival of plant pathogens, physical properties of soils, soil erosion, soil microbiology, and prevalence of nematodes, insects, mites, weeds, earthworms, and phytotoxins (Sumner 1982). Rotations are the primary means of maintaining soil fertility and achieving weed, pest, and disease control in organic farming systems. Although many rotations may be acceptable, they must conform to the following guidelines (Millington et al. 1990):

- Balanced fertility building and exploitative cropping
- Include a leguminous crop
- Include crops with different rooting systems
- Separate crops with similar pest and disease susceptibility
- Vary weed susceptible with weed suppressing crops
- Employ green manure crops and winter soil cover
- Increase soil organic matter content

Strategies using rotations have been used for incorporating diversity into cropping systems, for providing crop nutrients, and for managing pests in the field. The actual mechanisms that function in the plant and animal interactions emerging from rotations on a farm, determine what could be called the biological structuring of an agroecosystem.
Cropping systems that can be sustained with a greater dependence upon internal, renewable resources are based on a deeper understanding of the biological and natural environment and on the complex interactions among components in a cropping sequence. Efficient biological structuring depends upon these interactions and interdependencies among crops and other biotic factors. Many of the most intimate interactions occur among crops present in a field at the same time or those that overlap or follow each other (Figure 11.1). These complex interactions can be called the "progressive biological sequencing" in a field, the sum total of the linear and cyclical changes that occur in the field environment as a result of cropping activities and the soil modifications that occur as a result of the crops and their management (Francis and Clegg 1990).

Benefits and Effects of Rotating Crops

Up until the 1950s, wheat and cotton yields in California depended on internal sources and recycling of nitrogen and organic matter. Nitrogen was obtained by rotating these crops with legumes. Two types of legumes can be used to improve soil fertility, primarily through nitrogen contributions: annual seed legumes and perennial forages used as green manure crops. In fact, many farmers followed a fixed rotation system: a legume (alfalfa), a high-value crop (cotton), and a low-value grain (wheat). Alfalfa can produce up to 10 tons per hectare of dry matter and about 200 kg of nitrogen per hectare, sufficient to meet most of the nitrogen requirements of field and grain crops. In many parts of the United States' corn belt, alfalfa can provide up to 50 percent savings on nitrogen costs for the first corn crop after alfalfa. Of course, during its year in rotation the alfalfa also produces high-quality feed for livestock.

Today, it is common in the corn belt to alternate the two major cash crops, corn and soybeans. Corn yields (Table 11.1) were increased by 16 to 17 percent when grown after soybeans (Glycine max) compared to continuous maize (Francis and Clegg 1990). Early researchers concluded that rotation effects were due primarily to increased nitrogen availability after the soybean; more detailed research has shown this to be a primary factor, however, enhanced soil biological activity is also important. Nitrogen fixation by soybeans may vary from 57 to 94 kilograms per hectare per year. Longer rotations of more than two years might include a year each with a small-grain crop and a legume/grass mixture for a hay crop. Economics is often the major determinant of crop selection. Rotations can also suppress insects, weeds, and diseases by effectively breaking the life cycles of pests. "Break" crops provide effective control of pests and diseases, the effectiveness increasing with the length or frequency of breaks. In most cases, a one-year break is sufficient to provide control, but this depends on
FIGURE 11.1 Conceptual pattern of dynamic cyclical and linear changes in one environment as a result of successive crops and management decisions (after Edwards et al. 1986).

TABLE 11.1 Corn yields (kg ha$^{-1}$) following soybeans compared to continuous cropping of corn with no additional nitrogen fertilizer.

<table>
<thead>
<tr>
<th>Year(s)</th>
<th>Following Corn</th>
<th>Following Soybeans</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>1,483</td>
<td>4,089</td>
</tr>
<tr>
<td>1967–1984 (8 years)</td>
<td>5,259</td>
<td>8,412</td>
</tr>
<tr>
<td>1980</td>
<td>4,450</td>
<td>6,890</td>
</tr>
<tr>
<td>1982–1983 (2 years)</td>
<td>3,100</td>
<td>3,600</td>
</tr>
</tbody>
</table>

environmental conditions and on the particular pathogen or insect species (Bullen 1967; Table 11.2).

Organic rotations are designed to avoid factors which predispose toward damaging levels of pests and diseases. Successive crops of the same species are avoided, and crops with common pests and disease problems are not grown too close to each other in the rotation. The greater the botanical differences between crops in a rotation sequence, the better cultural control of pests can be expected. Rotation of summer annuals with winter annuals, perennial crops with annual crops, legumes with cereals, long-season with short-season crops are examples (Millington et al. 1990). For instance, red clover and winter beans are both susceptible to Sclerotinia trifolium, so should ideally not be grown in proximity to each other in the rotation.

Weed populations are especially sensitive to changes in crop species and herbicides used from one season to the next. As outlined above, the rotation of summer crops with winter crops is useful because it provides an opportunity to control both summer weeds and winter weeds. Rotation of a perennial with an annual crop also gives some cultural control of weeds not adapted to both systems (Francis and Clegg 1990).

The sequence of crops within a rotation may be critical since some crops yield better or worse depending on the crop they follow. Most experiments have documented the detrimental effects of continuous cropping of corn and
TABLE 11.2 Effect of crop rotation of corn on insect populations or potential damage (after Metcalf and Luckmann 1975).

<table>
<thead>
<tr>
<th>Crop Rotation</th>
<th>None</th>
<th>Soybeans</th>
<th>Pasture and Hay Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed corn beetles</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Seed corn maggot</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Wireworms</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>White grubs</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Corn root aphid</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Grape colaspis</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Northern corn rootworm</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Western corn rootworm</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Southern corn rootworm</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Black cutworm</td>
<td>0</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Billbug</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Slugs</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Thrips</td>
<td>0</td>
<td>?</td>
<td>+</td>
</tr>
<tr>
<td>Mites</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>European corn borer</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Southwest corn borer</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Corn earworm</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>True armyworm</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fall armyworm</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Chinch bug</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Corn leaf bug</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Totals</td>
<td>+</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>-</td>
<td>6</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>13</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>?</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

*+ means the practice will increase the population or damage from that insect; - means it will reduce the population or damage; 0 means no effect/ ? means effect unknown.*

Small grains on organic matter and nitrogen in unfertilized plots. Sorghum is a notoriously hard crop to follow. Yields of almost any crop after sorghum will be lower than after corn, soybeans, or wheat. It has been suggested that sorghum's effect on succeeding crops is due to the high carbohydrate content of sorghum's roots. The decomposition of the roots stimulates soil microbial growth and "ties up" nitrogen and other nutrients in the soil microflora, a
phenomenon known as immobilization. In other cases, the effect of one crop on the next may relate to chemicals left in the soil or generated by decomposition of the crop residues. Wheat residues, for example, have been shown to inhibit the growth of several different crops that might follow. The allelochemicals are thought to be produced during decomposition of the residues by certain soil microbes.

In turn, research has shown that plots that included a legume as a green manure increased yields of those crops. The benefits of green manuring is obtained by storing organic matter and nutrients in the soil by improvement crops and releasing the nutrients by decomposition of the organic matter when they are of the most benefit to the following crop. The most important contribution of winter legume cover crops, especially on sandy soils, was increased nitrogen (Doll and Link 1957). Throughout the United States, especially in areas with reasonably long frost-free seasons, a number of rotations have been developed (such as wheat/soybean/winter legume/corn, wheat/corn for silage; annual ryegrass grazed and allowed to reseed; soybeans/winter small grain/interseeded into summer crops).

In England, in mixed ley farming systems, the grass/clover ley period is expected to accumulate sufficient nitrogen by fixation to support subsequent arable crops. The nitrogen accumulated is made available to the succeeding crops through the microbial decomposition of the plant matter following cultivation of the ley. In addition, the return of manure and slurry from grazing and housed stock allows the movement of nutrients (particularly phosphorous and potassium) around the farm. The significant feature of such rotations is that the fertility building phase (the grass/clover ley) is economically productive since it supports a viable livestock enterprise (Briggs and Courtney 1985).

Maize yields after sweetclover are consistently greater than maize yields when fertilized with nitrogen. In a six-year experiment in Indiana, maize after sweetclover produced 5,952 kilograms per hectare, while maize with 94 kilograms of nitrogen per hectare produced 5,506 kilograms per hectare. Grain sorghum increased yields over four seasons when grown after sweetclover, with the greatest effect in the first year (Francis and Clegg 1990).

With the availability of inorganic fertilizers in modern agriculture, the need for crop rotation purely from the standpoint of soil fertility has diminished. The greatly increased supply of chemical nitrogen in the United States in the 1950s prompted much interest in continuous cropping. As prices of energy and nitrogen fertilizer increase, rotations may once again become cost effective, and substantial energy savings will surely ensue. Heichel (1978) showed that corn-based crop rotations incorporating grain and forage legumes reduce the demand for energy. Compared with continuous cropping, the fossil energy flux in rotations is reduced as much as 45 percent (Table 11.3).
TABLE 11.3 Intensity and efficiency of energy use in continuous corn compared with crop rotations incorporating grain and forage legumes (Heichel 1978).

<table>
<thead>
<tr>
<th>Rotation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Continous corn</td>
<td>2 Corn-soybeans</td>
<td>2 Corn-oats</td>
<td>2 Corn-alfalfa</td>
<td>3 Corn-soybeans</td>
<td>2 Corn-alfalfa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fossil energy flux (Mcal/a-day)</th>
<th>17.4</th>
<th>12.9</th>
<th>10.7</th>
<th>9.7</th>
<th>11.1</th>
<th>8.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop yield (lbs dry matter/a)</td>
<td>7,767</td>
<td>6,216</td>
<td>7,337</td>
<td>6,150</td>
<td>6,645</td>
<td>5,200</td>
</tr>
</tbody>
</table>

| Crop energy yield/fossil energy flux | 6.1 | 6.6 | 7.8 | 8.3 | 8.1 | 8.2 |

Obviously, the particular cropping sequence used in a rotation will vary with the climate, tradition, economics, and other factors. It should be expected, however, that crop rotations will broaden the economic base of the agricultural enterprise, spread labor demands more evenly through the year and allow production of high-value crops, thereby increasing income opportunities (Briggs and Courtney 1985). Rotations are very specific to each particular farm, and generalizations are usually of no real value. The following example from Scotland of a rotation of intensively farmed land with bought-in store cattle for fattening, shows the adaptation of the sequence to topography and climate making full use of livestock needs as well as a cash crop income (Widdowson 1987):

Year 1: Winter wheat. Cash crop following potatoes.
Year 2: Roots. For stock feeding—a cleaning crop after the cereal. Also, a crop to receive some farmyard manure.
Year 3: Spring barley. Cash crop utilizing residues after removal of the stock fed root. Nitrogen level will be low so a malting sample of barley is possible.

Year 4: Grass seed. Hay for stock.

Year 5: Spring oats. For stock feeding.

Year 6: Seed potatoes. A cash crop. Plenty of time to get good deep cultivations before planting, and the application of large quantities of farmyard manure made in the previous year.

The rotation utilizes half of the crops for stock and the other half for cash. The aim is to have two high-value cash crops, malting barley and seed potatoes. Potatoes are able to be sold for seed as the wind speeds are too high to allow aphid damage thus the possibility of virus infection is negligible. Livestock are presently purchased from the nearby stock rearers of the Highlands, but traditionally were purchased from Ireland (showing the multinational implications of holistic farming). The cattle are "finished" in covered cattle yards using the barley, oat, and wheat straw for the production of farmyard manure. Oat straw with hay is fed to the animals to ensure adequate roughage intake. Oat grain, together with roots and reject potatoes, complete the cattle diet. The nutrients supplied by this diet ensure that the livestock are sold off finished in that one winter. In this type of farming rotation, each crop lasts only one year.

Minimum Tillage Systems

Minimum tillage is any tillage system that reduces soil loss and conserves soil moisture, as compared with unridged or clean tillage (Mueller et al. 1981). Under this system unincorporated plant residues are left on the soil, and its surface is left as rough as possible. Most researchers consider conservation tillage to be any system which leaves 30% or more residue cover after planting. The various types include minimum tillage, chisel plowing, plow-plant, ridge tillage, and no-tillage. When successfully applied, these systems may reduce energy consumption and control erosion. Crop production using no-tillage methods has been shown to reduce material and energy inputs and, perhaps more importantly, to abate soil erosion. No-tillage systems also improve the scheduling and reliability of farm operations since many weather-related constraints are alleviated. General differences between both systems are depicted in Table 11.4. Crops grown by these practices can usually be planted, treated for weeds, and harvested when tilled fields would be too muddy to enter. Other advantages include moisture conservation, reduced soil compaction, and an increase in multiple-cropping potential. Furthermore, crop yields from no-tillage systems frequently equal or exceed the yields from conventional methods.
A USDA study estimated that by the year 2000, as much as 65 percent of the U.S. acreage of field grains—wheat, rye, and soybeans—will be produced by reduced tillage methods (Phillips et al. 1980).

The no-till system causes very little soil disturbance. The one-pass tillage and planting operation tills a slot approximately five cm wide for seed placement. The slot is usually opened with a fluted colter placed ahead of the planter unit. With no soil disturbance, more than 95 percent of the residue is left on the surface.

Effects on Soil Characteristics and Plant Growth

Soil Moisture. Tillage systems leaving 50 percent or more of the soil surface residue covered after planting generally increase soil moisture throughout the season due to increased filtration and decreased evaporation. In areas with low annual rainfall and on soils with low water-holding capacity, the added water should increase yield potential. On poorly drained soils in northern latitudes the extra water may delay planting and reduce yield potential (Sprague and Triplett 1986). Crops in mulch-covered, untilled soils experience less drought stress than in plowed soil during the growing season. Yields from tilled and untilled sites are similar during years of ample rainfall.

Soil Temperature. Several studies have shown that increased surface residue slows the rate of soil warming in the spring, therefore delaying germination, emergence, and early growth of crops, especially in the northern United States. However, this could be a benefit in the southern United States and in more tropical climates. Different types of tillage systems leave varying amounts of residue on the surface and, as a result, soil temperatures will vary among them. Differences in soil temperature between no-till and conventional practices can vary from 1° to 4° C.

Soil Fertility. Due to increased residue and reduced tillage, minimum tillage systems produce different levels of moisture, temperature, organic matter content, and rate of decomposition and microbial population. All these factors influence the availability of nutrients and thus the need for fertilizer. Leaving residues on the surface causes organic matter to build up near the soil surface, with positive effects on soil physical properties. Unfortunately, from the studies conducted thus far, researchers have not reached any conclusions as to whether nitrogen fertilizer programs must be changed for minimum tillage systems.

Some evidence suggests that surface residues left the first year after the adoption of no-tillage will exert a strong demand on available nitrogen and may cause deficiencies or at least lower nitrogen availability. However, after several years of minimum tillage, the system stabilizes and nitrogen fertility no longer varies from conventional tillage. In general, there is an increase in organic N in the 0 to 5 cm surface layer of the soil under no-tillage.
TABLE 11.4 Comparison of tillage effects on factors influencing crop productivity.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Plow-Tillage</th>
<th>No-Tillage</th>
<th>Effect of Crop*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil Factors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Warm days, cool nights</td>
<td>Little variation</td>
<td>+/-</td>
</tr>
<tr>
<td>Water intake</td>
<td>High following tillage, decreased with crusting</td>
<td>Lower initial rate maintained throughout season</td>
<td>+/-/o</td>
</tr>
<tr>
<td>Surface-applied minerals</td>
<td>Mixed with soil to plow depth</td>
<td>Percolate slowly</td>
<td>o</td>
</tr>
<tr>
<td>Bulk density</td>
<td>Decreased by primary tillage</td>
<td>Little effect</td>
<td>o/-</td>
</tr>
<tr>
<td>Compaction</td>
<td>Broken by tillage</td>
<td>Little disturbance</td>
<td>-</td>
</tr>
<tr>
<td>Aeration</td>
<td>Initial increase</td>
<td>Little effected</td>
<td>o/-</td>
</tr>
<tr>
<td>Organic matter distribution</td>
<td>Mixed with soil</td>
<td>Near surface</td>
<td>-</td>
</tr>
<tr>
<td><strong>Biological Factors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weed control</td>
<td>Initially excellent</td>
<td>Reliance on herbicides</td>
<td>-</td>
</tr>
<tr>
<td>Disease organisms</td>
<td>Inoculum buried</td>
<td>At surface</td>
<td>-</td>
</tr>
<tr>
<td>Soil invertebrates</td>
<td>Disrupts life cycle</td>
<td>Little effect</td>
<td>+</td>
</tr>
<tr>
<td>beneficial</td>
<td>Same as beneficial</td>
<td>Little effect</td>
<td>-</td>
</tr>
<tr>
<td>destructive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Machine Function</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planting</td>
<td>Machine designed for loose soil</td>
<td>Special equipment for undisturbed soil</td>
<td>o/-</td>
</tr>
<tr>
<td>Cultivation</td>
<td>Effective in loose soil, root pruning</td>
<td>More difficult in mulch</td>
<td>o/-</td>
</tr>
<tr>
<td><strong>Management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic support</td>
<td>Poor</td>
<td>Good</td>
<td>+</td>
</tr>
<tr>
<td>(in wet soil)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timely operations</td>
<td>May be delayed</td>
<td>More time to be reliable</td>
<td>+</td>
</tr>
<tr>
<td>Power demand</td>
<td>Increased by successive operations</td>
<td>Minimal</td>
<td>N/A</td>
</tr>
<tr>
<td>Labor demand</td>
<td>Increased by successive operations</td>
<td>Minimal</td>
<td>N/A</td>
</tr>
<tr>
<td>Dependability</td>
<td>Good</td>
<td>Can be erratic</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Code: + positive benefit for no-till; o neutral or no effect; - no-till detrimental; N/A not applicable.

Phosphorus seems to have equal or greater availability under no-till compared with the conventional system, regardless of whether the fertilizer was broadcast or banded. This phenomenon occurs despite the fact that broadcast phosphorus accumulates in the top centimeter of the soil under no-till because of the lack of incorporation and movement through the soil.
profile. Possibly the residues on the surface allow sufficient moisture for root growth and uptake of phosphorous nutrients.

There is disagreement about the availability of potassium under no-tillage. Some researchers have found decreased available potassium, especially under some wet and cold conditions, while others have reported no deficiency. Further research should clarify these conflicting views, however, continual applications of potassium fertilizer leads to a buildup of K in the top 5 cm soil layer under no-till management (D'Itri 1985).

**Soil Acidity.** Soil acidity becomes a greater factor under no-tillage. An issue is the airification of the soil surface where nitrogen fertilizer is applied. Low pH levels near the soil surface can lead to crop yield losses due to nutrient indolence and additional weed competition. The rapid lowering of soil pH is less of a problem when legumes are used which demand less N fertilizer. Of the secondary and microelements, magnesium is little affected and sulfur is likely to be less available from the soil organic matter. Zinc tends to be more available due to higher organic matter content and lower pH. In general, soil fertility under no-tillage is strongly influenced by the interacting effects of increased soil moisture, high levels of slowly decomposing organic matter in the soil, higher acidity, and lower temperatures in the spring (Sprague and Triplett 1986). The identification of crops that leave surface residues with allelopathic activity against a broad range of weed species is a major challenge.

**Effects on Pests**

**Weed Control.** Conservation tillage systems depend on heavy applications of herbicides. Usually the maximum recommended herbicide rate is used in corn because of the surface accumulation of weed seeds, which potentially exert greater weed pressure than under conventional tillage. In addition, surface residue intercepts and inactivates part of the applied herbicide.

Eliminating tillage causes shifts in weed species. Perennials readily controlled by tillage become established and persist in untilled fields. Weeds botanically related to the crop and others that escape control often increase, becoming major problems. A classic example is the increase of fall panicum in corn after repeated applications of atrazine to control annual weeds in no-till systems (Sprague and Triplett 1986).

**Disease Control.** Alterations of the microclimate due to surface residues may retard, enhance, or have no effect on plant diseases. The degree of influence on plant diseases by residue generally relates to the amount of residue remaining after planting. Surface residues may affect plant diseases in several ways. They provide a habitat for overwintering (survival), growth, and multiplication of plant pathogens, particularly fungal and bacterial pathogens. There are many plant pathogens that overwinter best in
surface residues because they are protected from the environment and other microorganisms. Surface tillage increases the chances of epidemics caused by such pathogens. During a seven-year study, foliar diseases were never observed to be a problem on grain sorghum or wheat grown under minimum tillage in Nebraska (Doupnik and Boosalis 1980). The incidence of stalk rot of grain sorghum, a stress disease caused by *Fusarium moniliforme*, was dramatically reduced under no-tillage compared with that under conventional tillage. Its incidence was reduced from 39 percent to 11 percent, and yield was increased (Sprague and Triplett 1986). The increased soil moisture storage and the lower, more constant soil temperature associated with minimum tillage are undoubtedly two major factors accounting for the lower incidence of stalk rot in corn. Under these more favorable growing conditions, the plants are less vulnerable to this fungus. On the contrary, in Wisconsin, eyespot (a leaf disease of corn) has been shown to be more severe on corn grown under no-tillage.

Crop rotation is especially important for controlling diseases with surface tillage. Planting a crop in its own residue from the previous season without a fallow period is more likely to increase certain plant diseases than a system in which a crop is planted into the residue of an unrelated crop. Another way to reduce diseases associated with reduced tillage is to rotate tillage systems. Tillage rotation plus crop rotation is an excellent method of disease management. This could be done in a manner to allow retention of 20 to 30 percent of the surface residue, thus providing the benefits of surface tillage while reducing the potential of disease outbreak.

Soil-borne fungal diseases associated with surface tillage may be decreased by the kind, amount, and time of fertilizer application. Applying ammonium sulfate in the spring controlled take-all of wheat, whereas fall application of nitrogen for spring-seeded wheat increased take-all.

**Insect Dynamics.** Entomologists working in no-till agriculture found that the mulch-litter layer of no-tillage soil provides a favorable microhabitat for insects that attack corn, such as army worms, black cutworm, and stalk borers (House and Stinner 1983). The loss of reliable mechanical destruction methods in no-tillage corn increases the survival of insect pests inhabiting crop residue or residing on or near the soil surface. The greatest hazard for pest infestation occurs in the seed and seedling stages from subterranean insect pests. Two pest trends are often associated with no-tillage systems: (a) the level of pest activity is related to the previous crop type, and (b) no-tillage systems support a higher diversity of pest insects than conventional tillage systems. Most approaches to solving pest problems in no-tillage systems have been largely symptomatic. Almost exclusive reliance has been placed on broad spectrum insecticides, and little research has been devoted to developing cultural and biological methods of pest suppression and prevention.
Recently, investigators in Georgia have reported entomologically beneficial aspects inherent to no-tillage systems (House and Stinner 1983). For example, the lesser corn stalk borer *Elasmopalpus lignosellus* feeds preferentially on grain stalk residues in no-tillage corn systems. Thus, infestations of the lesser corn-stalk borer are deterred. In tropical Costa Rica, Shenk and Saunders (1983) found that incidence of the fall armyworm (*Spodoptera frugiperda*) and the leaf beetle (*Diabrotica balteata*) was much greater in plowed maize plots than in no-till plots. In north Georgia soybeans, the abundance and diversity of carabid beetles are often several times higher in no-tillage than in conventional tillage soybeans. The surface litter and weeds on no-tillage usually provide the predatory carabid and spider fauna with greater food resources as well as protection from unfavorable climatic conditions (House and Stinner 1983). Their control of some seed and seedling weed populations can be substantial. Increased moisture and reduced temperature can enhance development of insect pathogens, as it was observed with rhabditoid nematodes in no-till sorghum (Sprague and Triplett 1986).

**Crop Yields**

Despite the variability in yield response between no-till and tilled systems, some generalizations are possible:

1. The surface residue left with conservation tillage reduces both evaporation and runoff of water. In areas where inadequate rainfall is the principal factor limiting plant growth, the moisture-conserving feature of a surface mulch is a distinct plus and likely accounts for the high percentage of land in conservation tillage in the U.S. Northern Plains.

2. Surface residue and associated increase in soil moisture slows soil warming in spring, delaying seed germination and seedling emergence. Where the growing season is already short, as at high latitudes, this characteristic of conservation tillage provides a yield disadvantage.

3. Conservation tillage generally suffers a yield disadvantage on poorly drained soils. Apparently, soil wetness is the most important single soil factor restricting adoption of conservation tillage in the Cornbelt and becomes less restrictive as one moves from east to west. Disease organisms and weeds, favored by moist environments, are reasons for poor yield on poorly drained soils; cold, moist soil conditions also slow mineralization of organic nitrogen and facilitate denitrification and breakdown of herbicides by soil bacteria.

4. Reduced tillage systems suffer a yield penalty wherever weeds are not adequately controlled by herbicides. Perennial weeds in particular may become troublesome because they are less vulnerable than annuals to herbicides due to below-ground regeneration.
5. Conservation tillage saves time between harvesting one crop and planting of another, and so is more favorable to double cropping than plow-tillage. Taking two crops per year from the land instead of only one increases the economic yield of the land. This advantage is most marked in the U.S. southeast, where stretching of the already long growing season favors double cropping. It is practiced also in parts of the southern Cornbelt.

Energy Requirements

Less energy is required for tillage operations in many no-till systems. Energy savings benefits of conservation tillage are (a) less fuel consumption due to reduced field operations, (b) less time and labor required, (c) possibility of double cropping, and (d) lower investment in farm machinery. Yet some activities such as higher herbicide use and special seeding rates and equipment demand more energy. Since plowing, diskng, and other trips over the field are eliminated, these systems result in 34 percent to 76 percent reductions in fuel for tillage operations. However, the requirement for additional herbicides in no-tillage systems may offset some of these gains. In general, though, total production costs for corn in the midwest United States rise slightly with the intensity of tillage. Research on crop rotations including crops that leave residues with allelopathic activity against certain weeds (Chapter 14) is clearly warranted to reduce herbicide use in no-tillage systems. Many annual broadleaf weeds are suppressed if mulches, especially small grain cover crops are left on the soil surface (Putnam and DeFrank 1983). Fall-dessicated "Balboa" rye and "Tecumseh" wheat used in rotations can greatly reduce weed biomass in the next growing season by inhibiting germination and growth of several weed species.

Designing Conservation Tillage or Ecofallow Systems

Some form of conservation tillage can be applied to a wide range of soils and ecological regions by adopting a holistic approach that considers all factors that affect production (D'Itri 1985). Conservation tillage requires a special set of cultural practices that may be different from those needed for plow-based tillage (Figure 11.2). Careful consideration should be given to the set of cultural practices specifically developed for conservation tillage. Conservation tillage is not just a concept but a package of cultural practices that are specifically developed and adopted to conserve soil and water resources, sustain high and satisfactory returns, minimize degradation of soil and environment, and maintain the resource base.
FIGURE 11.2 Cultural practices needed for successful adoption of conservation tillage.
Agroforestry Systems

John G. Farrell and Miguel A. Altieri

Agroforestry is the generic name used to describe an old and widely practiced land use system in which trees are combined spatially and/or temporally with agricultural crops and/or animals. It combines elements of agriculture with elements of forestry in sustainable production systems on the same piece of land. However, only recently have modern concepts of agroforestry been developed, and to date no universally acceptable definition has evolved, although many have been suggested including ICRAF's definition: "Agroforestry denotes a sustainable land and crop management system that strives to increase yields on a continuing basis, by combining the production of woody forestry crops (including fruit and other tree crops) with arable or field crops and/or animals simultaneously or sequentially on the same unit of land, and applying management practices that are compatible with the cultural practices of the local population." (International Council for Research in Agroforestry 1982). Whatever the definition, it is generally agreed that agroforestry represents a concept of integrated land use that is particularly suited to marginal areas and low-input systems. The objective of most agroforestry systems is to optimize the beneficial effects of interactions of the woody components with the crop or animal component to obtain a production pattern that is compared to what is usually obtained from the same available resources under monoculture given prevailing social, ecological, and economic conditions (Nair 1982).

Characteristics of Agroforestry

Agroforestry incorporates four characteristics:

Structure. Unlike modern agriculture and forestry, agroforestry combines
trees, crops, and animals. In the past, agriculturalists rarely considered trees useful on farmland, while foresters have regarded forests simply as preserves for growing trees (Nair 1983). Yet for centuries traditional farmers have provided for their basic needs by raising food crops, trees, and animals together.

**Sustainability:** Agroforestry optimizes the beneficial effects of interactions between woody species and crops or animals. By using natural ecosystems as models and applying their ecological features to the agricultural system, it is hoped that long-term productivity can be maintained without degrading the land. This is particularly important considering the current application of agroforestry to areas of marginal land quality and low availability of inputs.

**Increased Productivity:** By enhancing complementary relations among farm components, improved growing conditions, and efficient use of natural resources (space, soil, water, light), production is expected to be greater in agroforestry systems than in conventional land use systems.

**Socioeconomic/Cultural Adaptability:** Although agroforestry is appropriate to a wide range of farm sizes and socioeconomic conditions, its potential has been particularly recognized for small farmers in poor, marginal areas of the tropics and subtropics. Considering that peasants are usually unable to adopt modern, high-cost agricultural technologies, have been bypassed by agricultural research, and have no discernible political or social power, agroforestry is particularly adapted to the circumstances of small farmers.

**Classification of Agroforestry Systems**

Several criteria can be used to classify agroforestry systems and practices (Nair 1985). Most commonly used are the system's structure (composition and arrangement of components), function, socioeconomic scale, level of management, and ecological spread. Structurally, agroforestry systems can be grouped as:

- **Agrisilviculture:** the use of land for concurrent or sequential production of agricultural crops and forest crops
- **Silvo-pastoral systems:** land management systems in which forests are managed for the production of wood, food and fodder, as well as for the rearing of domesticated animals
- **Agro-silvo-pastoral systems:** systems in which land is managed for the concurrent production of agricultural and forest crops and for the rearing of domestic animals
- **Multipurpose forest tree production systems:** in which forest tree species are regenerated and managed for the ability to produce not only wood, but leaves and/or fruit that are suitable for food and/or fodder
Other agroforestry systems can be specified, such as apiculture with trees, aquaculture in mangrove areas, multipurpose tree lots, and so on. The components can be arranged in time or space, and several terms are used to denote the various arrangements. Functional basis refers to the main output and role of components, especially the woody ones. These can be productive functions (production of basic needs, such as food, fodder, fuelwood, other products) and protective roles (soil conservation, soil fertility improvement, protection offered by windbreaks and shelterbelts).

On an ecological basis, systems can be grouped for any defined agroecological zone such as lowland humid tropics, arid and semi-arid tropics, tropical highlands, and so on. The socioeconomic scale of production and level of management of the systems can be used as the criteria to designate systems as commercial, intermediate, or subsistence. Each of these criteria has merits and applicability in specific situations, and each also has limitations, so no single classification scheme can be considered universally applicable. Classification will depend on the purpose for which it is intended.

*The Potential Role of Trees*

Trees are generally underused in agriculture, and although much has been written of their virtues (Smith 1953, Douglas and Hart 1976, MacDaniels and Lieberman 1979), their potential has gone relatively unexplored. By virtue of their form and growth habit, trees influence other components of the agricultural system (Figure 12.1). Their large canopies affect solar radiation, precipitation, and air movement, while their extensive root systems fill large volumes of soil. Absorption of water and nutrients and the redistribution of nutrients as leaf litter, as well as the disruptive movement of the roots and possible root fungal/bacterial associations, can also alter the growing environment.

Trees can enhance the productivity of a given agroecosystem by influencing soil characteristics, microclimate, hydrology, and other associated biological components.

**Soil Characteristics.** Trees may affect the nutrient status of the soil by exploiting the deeper mineral reserves in the parent rock and by retrieving leached nutrients and depositing them on the surface as leaf litter. This organic matter increases the soil humus content, which in turn increases its cation exchange capacity and decreases nutrient losses. The added organic matter also moderates extreme soil reactions (pH) and the consequent availability of both essential nutrients and toxic elements. Since nitrogen, phosphorus, and sulfur are primarily held in organic form, plenty of organic matter is especially important to make them available. The association of trees with nitrogen-fixing bacteria and mycorrhizae will also increase available nutrient levels. Microorganism activity tends to increase under trees
FIGURE 12.1 The influence of trees in Tlaxcala, Mexico, on the growing environment of corn (Farrell 1984).
because of increased organic matter (improved food supply) and growing environment (soil temperature and moisture).

A study conducted to evaluate the role of trees in traditional farming systems of Central Mexico (Farrell 1984) illustrates the potential influence of trees on soil fertility. Surface soil properties were measured at increasing distances from two tree species, capulin (Prunus capuli) and sabina (Juniperus deppeana), found within selected crop fields. Higher values of all properties measured were found under the capulin canopies, and a decreasing gradient was observed with increasing distance from the trees. Available phosphorous increased fourfold to sevenfold under the trees (Figure 12.2) and

![Graph showing change in surface soil nitrogen and phosphorus with increasing distance from individual capulin and sabino trees.](image)

**FIGURE 12.2** Change in surface soil nitrogen and phosphorus with increasing distance from individual capulin and sabino trees (Farrell 1984).
total carbon and potassium increased two to threefold; nitrogen, calcium, and magnesium increased one and a half to threefold and cation exchange capacity increased one and a half to twofold. Soil pH was also found to be higher under the canopies. This spatial pattern was attributed primarily to the redistribution of nutrients with litter fall and the accumulation of organic matter near the capulin trees.

Trees may also enhance the physical properties of soil, the most important being soil structure. Structure improves as a result of increased organic matter (leaves and roots), and the disruptive action of the tree’s roots and microorganism activity, all of which aid in developing more stable soil aggregates. Soil temperature is moderated by the shade and litter cover.

The role trees may play in soil protection is well recognized. In addition to reducing wind velocities, the tree canopy diffuses the impact of rain drops hitting the soil surface. The litter layer covering the soil and its improved structure also help reduce surface erosion. The penetrating root system of trees serves an important function in stabilizing the soil, especially on steep slopes.

The inclusion of compatible and desirable species of woody perennials on farmlands can result in a marked improvement in soil fertility through the following:

1. Increase in the organic matter content of soil through addition of leaf litter and other plant parts
2. An efficient nutrient cycling within the system and consequently more efficient utilization of both native as well as costly applied nutrients
3. Biological nitrogen fixation and solubilization of relatively unavailable nutrients, for example, phosphate through the activity of mycorrhizae and phosphate-solubilizing bacteria
4. Increase in the plant cycling fraction of nutrients and resultant reduction in the loss of nutrients beyond the nutrient absorbing zone of the soil
5. Complementary interaction between the component species of the system, resulting in more efficient sharing of nutrients among the components
6. Additional nutrient economy because of different nutrient absorbing zones of the root systems of the component species
7. Moderating effect of soil organic matter on extreme soil reactions and consequent nutrient release/availability patterns

**Microclimate.** Trees moderate temperature changes, resulting in lower maximum and higher minimum temperatures under trees as compared with open areas. Lowered temperature and reduced air movement due to tree canopy reduces the evaporation rate. Greater relative humidity may also be found under trees compared with open sites.
**Hydrology.** The water balance of a given microsite, farm, or region is influenced by both structural and functional characteristics of trees. To varying degrees, depending on canopy density and leaf characteristics, precipitation either passes through to the soil surface, is intercepted and evaporates, or is redistributed to the base of the trunk with stemflow. Air moisture may also be collected by tree canopies and deposited as internal precipitation (fog drip), a potentially significant source of water in moist foggy areas. As a result of improved soil structure and the presence of a litter layer, the water that does reach the ground is used more efficiently due to increased infiltration and permeability, and evaporation and surface runoff are reduced. On a larger scale, particularly in areas prone to flooding, trees may reduce subterranean water discharge, and there is evidence that the hydrological characteristics of catchment areas are favorably influenced by the presence of trees.

**Associated Biological Components.** Crop and non-crop plants, insects, and soil organisms can benefit from the presence of compatible trees. Although the specific mechanisms are little understood, they generally involve a more benign microclimate; favorable soil temperature, moisture regime, and organic matter status; and increased availability of nutrients, as well as their efficient use and recycling. The improvement in organic matter status of the soil can result in increased activity of favorable microorganisms in the root zone. Such microorganisms may also produce growth-promoting substances through desirable interaction and cause commensalistic effects on the growth of plant species.

**Productive Role.** Trees produce a number of products important to both humans and animals. In addition to food and forage, they provide wood products, by-products such as oils and tannins, and medicinal products. For example, the black locust (*Robinia pseudoacacia*) is an important honey plant, fixes nitrogen and is a source of durable fenceposts. *Leucaena*, another nitrogen-fixing legume, is valuable as poultry and cattle food in the tropics because of its high vitamin and protein content. It is also a primary source of firewood (NAS 1977). Tree crops can also supplement grain production. Species such as chestnut (*Castanea*), carob (*Ceratonia*), and honey locust (*Gleditsia*) have a higher food value in proteins, carbohydrates, and fats than some conventional grains (Smith 1953), and also grow on marginal land without cultivation.

**Advantages of Agroforestry Systems**

By combining agriculture and forestry production, various functions and objectives of forest and food crop production can be better achieved. There are environmental as well as socioeconomic advantages of such integrated systems over agriculture and/or forestry monocultures. (Wiersum 1981).
Environmental Advantages

1. A more efficient use is made of the natural resources. The various vegetation layers provide for an efficient utilization of solar radiation, different kinds of rooting systems at various depths make good use of the soil and short-lived agricultural plants can profit from the enriched topsoil as a result of the mineral cycling through treetops. By including animals in the system, unused primary production can also be utilized for secondary production and nutrient recycling.

2. The protective function of trees in relation to soil, hydrology, and plant protection can be utilized to decrease the hazards of environmental degradation. It should be kept in mind, however, that in many agroforestry systems the components may be competitive for light, moisture, and nutrients, therefore, trade-offs must be considered. Good management can minimize this interference and enhance the complementary interactions.

Socioeconomic Advantages

1. By ecological efficiency the total production per unit of land can be increased. Although the production of any single product might be less than in monocultures, in some instances production of the base crop may increase. For example, in Java it has been demonstrated that after introduction of the taungya system, dryland rice production increased significantly.

2. The various components or products of the systems might be used as inputs for production of others (for example, wooden implements, green manure) and thus the amount of commercial inputs and investments can be decreased.

3. In relation to pure forestry plantations, the inclusion of agricultural crops, coupled with well-adjusted intensive agricultural practices, often results in increased tree production and less costs for tree management (e.g., fertilization and weeding of agricultural crops may also benefit tree growth) and provide a wider array of products.

4. Tree products can often be obtained throughout the year providing year-round labor opportunities and regular income.

5. Various tree products can be obtained in the agricultural off-season (e.g., dry season), when no opportunities for other kinds of plant production are present.

6. Some tree products can be obtained without much active management, giving them a reserve function for periods of failing agricultural crops, or special social necessities (e.g., building a house).

7. By the production of various products a spreading risk is obtained, as these products will be affected differently by unfavorable conditions.

8. Production can be directed toward self-sufficiency and marketing. The
dependency on the local market situation can be adjusted according to the farmer's need. If so desired, the various products are entirely or partially consumed, or delivered to the market when conditions are right.

**Some Constraints of Agroforestry Systems**

There are a number of limiting conditions or constraints to implementing agroforestry systems. These constraints should be recognized and efforts made to overcome them, if agroforestry is to be applied successfully.

A major constraint is that agroforestry systems are ecosystem-specific and on certain low grade soils the choice of suitable plant species might be limiting, although many trees are better adapted to poor soils than annual crops. The competition between trees and food crops and the priority that must be given to them to meet basic needs may exclude poor farmers, who have very little land, from tree growing.

In promoting tree planting, short-term benefits as well as long-term benefits are needed. Economic or production incentives need to be included. A common economic constraint is that some newly established agroforestry systems might need substantial investment costs to get started (e.g., planting material, soil conservation, fertilizer). For these investments, credit may be needed. In most agroforestry systems one may need a few years before the first yields are obtained. In some cases, financial support is needed to provide for this waiting period.

Size of plot may affect the kind of inputs. In areas with a high population pressure and poor soils, the private landholdings might be too small as viable production units. In this case some kind of cooperative effort might be necessary. Availability of seeds and/or seedlings is a critical variable for agroforestry projects. In most cases, longer run planning includes developing small nurseries along with planting and maintaining trees.

Management of livestock sometimes can conflict with agroforestry ventures especially in areas where cattle or goat herding is being practiced. In areas with complex clan or communal land systems, developing agroforestry systems may be difficult. Tenure rights are a fundamental consideration in agroforestry. They may be a limiting factor.

Tree tenure is also a possible constraint. In any case, land on which trees may be planted and protected is not owned by those who planted them. The planters, then may not be legally entitled to harvest the trees or the produce of the trees. Further, in some countries there are laws that restrict the harvesting/cutting of trees for any purpose regardless of who owns the land on which they are planted.
Designing Agroforestry Systems

Natural ecosystems can be useful as models for designing sustainable agricultural systems. The most conspicuous feature of natural forests is their multistoried organization of trees, shrubs, forbs, and fungi, each using different levels of energy and resources and each contributing to the functioning of the entire system. These layers lessen the mechanical impact of raindrops hitting the soil surface and reduce the amount of direct sunlight reaching the ground, thereby minimizing the potential for soil loss, reducing evaporation and slowing the rate of organic matter decomposition. There is generally little wind at ground level. On the soil surface, decaying plant litter provides a protective cover and a source of nutrients to be recycled (Figure 12.3).

All these conditions create an ideal environment for microflora and fauna, insects and earthworms that promote the decay and incorporation of organic matter into the soil, creating good soil structure, which in turn enhance aeration and water filtration. Insects that are potentially harmful to the vegetation are kept in check by resident predators and parasites. There is also multilayering below the surface, where the roots of various plant forms use different soil volumes. Thus, nutrients that are leached below the rooting zone of the smaller vegetation are intercepted by the deeply penetrating roots of trees and returned to the surface as leaf litter.

The main goal in designing an agroforestry system is to enhance the fundamental ecological features of the forest, so an understanding of these processes in a natural system is essential. Most of the principles outlined in Chapter 5 can be applied to designing agroforestry systems, particularly Hart's ideas (1978) about designing crop sequences analogous to natural succession. In the humid tropics successional ecosystems can be particularly appropriate models for the design of agricultural ecosystems. In Costa Rica, plant ecologists conducted spatial and temporal replacements of wild species by botanically and/or structurally/ecologically similar plants. Thus, successional members of the natural system such as Heliconia species, cucurbitaceous vines, Ipomea species, legume vines, shrubs, grasses and small trees were simulated by plantain, squash varieties, yams, sweet potatoes, local bean crops, Cajanus cajan, corn/sorghum/rice, papaya, cashew, and Cassava species, respectively. By years two and three, fast-growing tree crops (for example, Brazil nuts, peach palm, rosewood) may form an additional stratum, thus maintaining continual crop cover, avoiding site degradation and nutrient leaching and providing crop yields throughout the year. This approach can be very useful in regions lacking natural vegetation, where successional models from ecologically homologous areas can be initiated. Oldeman (1981) proposed the "transformation" concept as another design option. Complementary to the analog approach, its base is the structural analysis
FIGURE 12.3 Schematic presentation of nutrient relations and advantages of ideal agroforestry systems in comparison with common agricultural and forestry systems (after Nair 1982).
analysis of collective units (eco-units). Transformation may be brought about by replacing wild species with useful species fulfilling the same functional and structural niche as their wild precedents. This process transforms the structure of the natural system while maintaining its beneficial properties.

In situations where a fully forested area is not suitable for a farm, trees may be combined with crops and animals in other ways to enhance the desired functional relationships. Wiersum (1981) and Combe and Budowski (1979) have outlined these practices in their attempts to develop a classification system for agroforestry techniques.

**Plant Arrangements**

A number of factors should be considered in arranging component plant species in space and time. These may include the cultural requirements of component species when grown together, their growth form (both above and below ground) and phenology, management requirements for the entire system, and the need for additional actions such as soil conservation or micro-climate amelioration. Thus, plant arrangement patterns are site specific. Possible patterns include (Nair 1983):

1. Intercropping tree species with annual agricultural crops, planting both herbaceous and woody species simultaneously (or in the same season). The spacing of woody species will vary considerably but generally they will be spaced more widely in drier regions. This scheme can also be applied to agricultural plantation crops such as rubber and oil palm.

2. Clearing strips about one meter wide in primary or secondary forests at convenient intervals and planting shade-tolerant perennial agricultural species such as cacao. Subsequently, as the planted species grow up, the forest vegetation will be selectively thinned, and in about five years there will be a two or three layer canopy consisting of the perennial agricultural species and the selected forestry species.

3. Introducing management practices such as thinning and pruning to allow more light to penetrate to the plantation floor and planting selected agricultural species between the rows of trees. The extent of thinning or pruning will depend upon the tree density, canopy structure and so forth.

4. In hilly areas, selected tree species can be planted in lines across the slope (along the contour) in different planting arrangements (single rows, double rows, alternate rows), with varying distances between rows; soil-binding grasses can be established between the trees along the contours. The area between the rows can be used for agricultural species.

5. Close-planting multipurpose trees around plots of agricultural fields. The trees will form live fences and windbreaks, provide fodder and fuel, and mark the boundaries of agricultural plots. The scheme is particularly suitable for extensive land use areas.
6. Interspersing intensively managed agricultural areas with trees, in a regular or haphazard manner. The system is popular in smallholder farming in Asia, the Pacific, Africa, and South America.

**Examples of Agroforestry**

Home gardens in the tropics are one of the classic examples of agroforestry. Home gardens are a highly efficient form of land use, incorporating a variety of crops with different growth habits. The result is a structure similar to tropical forests, with diverse species and a layered configuration. Throughout the tropics, traditional agroforestry systems may contain well over 100 plant species per field. These are used for construction materials, firewood, tools, medicine, livestock feed, and human food. In Mexico, for example, Huastec Indians manage a number of agricultural and fallow fields, complex home gardens, and forest plots totalling about 300 species. Small areas around the houses commonly average 80–125 useful plant species, mostly native medicinal plants. Management of the noncrop vegetation by the Huastecs in these complex farm systems has influenced the evolution of individual plants and the distribution and composition of the total crop and noncrop communities. Similarly, the traditional pekarangan system in West Java, described in Chapter 6, commonly contains about 100 or more plant species. Of these plants, about 42% provide building materials and fuelwood, 18% are fruit trees, 14% are vegetables, and the remainder constitute ornamentals, medicinal plants, spices, and cash crops.

Intensive intercropping with plantation crops such as coconut, cacao, coffee, and rubber is another agroforestry technique. In India, crops such as black pepper, cacao, and pineapple are grown under the coconut, using the available light as well as a greater percentage of soil volume (Nair 1979). Coffee, tea, and cacao, are traditionally grown under one or two strata of shade trees; these often are nitrogen-fixing legumes that also produce valuable wood products.

In semi-arid and arid parts of the world, the use of multipurpose trees mixed with crops or as part of pastoral systems is the dominant agroforestry practice. Species such as *Acacia* and *Prosopis* are valuable, not only for their wood products and forage, but also for their soil-enriching qualities. The unique phenology of *Acacia albida* (leafless during the rainy season) makes it an ideal component of the sorghum- and millet-producing regions of West Africa and the Sahelian zone.

Similar uses of trees have been described in Mexico (Wilken 1977), where farmers encourage the growth of native leguminous trees in cultivated fields. From Puebla and Tehuacan south through Oaxaca, farms with light to moderately dense stands of mesquite (*Prosopis* spp.), guaje (*Leucaena esculenta*),
and guamuchil (*Pithecellobium* spp.) are a familiar site. Stand density varies from fields with only a few trees to virtual forests with crops planted beneath.

A slightly different practice is found near Ostuncalco, Guatemala, where rigorously pruned sauco (*Sambucus mexicana*) stumps dot maize and potato fields. Leaves and small branches are removed annually, scattered around individual crop plants, then chopped and interred with broad hoes. Local farmers claim that crop quality and yields in the sandy volcanic soils of this region depend upon these annual applications of sauco leaves.

Trees are integrated with farm animals in many areas. They range from small animals confined to home gardens in the tropics, to livestock grazing in orchards in Chile (Altieri and Farrell 1984) to livestock grazing in forest plantations in New Zealand (Tustin et al. 1979) or the southeastern United States (Lewis et al. 1984).

**Agroforestry Management Options**

**Alley Cropping in High Potential Areas**

Alley cropping is appropriate for home gardens and for cultivated arable land. This system can be helpful in the following ways:

- Providing green manure or mulch for companion food crops and recycling plant nutrients from deeper soil layers
- Providing prunings, applied as mulch, and shade during the fallow season
- Suppressing weeds
- Providing favorable conditions for soil macro- and microorganisms; when planted along the contours of sloping land to provide a barrier for soil erosion control
- Providing prunings for browse, staking material, and firewood
- Providing biologically fixed nitrogen to the companion crop

**Contour Planting**

Contour planting is useful where there are the following conditions:

- Poor or easily depleted soils
- Sloping (erodible) land as well as non-erodible land
- Medium to high population density

Contour planting can help in the following ways:

- To restore/improve soil nutrient and increase organic material content
To reduce soil and water run-off
To spread the risk of crop failure during extremely dry seasons by moderating the effects of excessive moisture evaporation on exposed land
To add wood products for home consumption or sale

The appropriate farming system in which to utilize this system is a permanent crop cultivation, medium to small farm size, and medium to high labor input available per unit of land. Fast growing species can be established at the start of the growing season, which gives them the opportunity to establish while livestock are kept out of the arable areas.

**Fodder Bank—Cut and Carry**

Establishment of fodder banks is useful where there is a high population density and nearby markets for livestock products. Fodder banks can improve fodder availability and quality, particularly during the late dry and early wet season. They can restore/improve soil nutrients and organic matter content.

Creating these banks of trees will facilitate ease of fencing. Pure stands (blocks, strips, lines) of trees (mainly leafy fodder) can be planted near cattle kraals, in homestead gardens, in arable land and grazing areas, along watercourses, and around the margins of watering places. The appropriate farming system for fodder banks is on small farms, where there is intensive land use, a kraal feeding system, and high labor input per animal.

**Fodder Bank—Grazing**

Fodder banks for grazing are usually located in grazing areas. They may be on hills (especially pod species), on upland along watercourses, and on borders of watering species.

Fodder banks for grazing will improve fodder availability and quality in low to medium population density areas and restore/improve soil nutrients and level of organic materials.

A mixture of trees (pods and leaves) and grasses (fenced) can be planted in blocks. Pod and foliar species should be planted along hedges. Scattered trees need to be protected by thorns. The species will provide a feed supplement for cattle during the rains.

Species selected must be adaptable to local climate and soil as well as having other attributes such as palatability, high protein content, and ease of establishment by direct seeding or transplanting. Pod trees for hills and uplands seed from August to December. Self-seeding varieties in watering places must be tolerant of up to six months waterlogging.
**Fruit Improvement**

In the homestead arable area and garden it is useful to add fruit-producing trees. Scattered trees, planted near the home will allow for protection from animals. Fruit trees may also be planted to create boundaries around the homestead. This will improve nutrition, produce fruit for sale, and provide shade and firewood.

Use of the system is limited by the availability of improved fruit varieties. There needs to be adequate extension support to help with choice of varieties and management (e.g., propagation, grafting and budding, planting, mulching, watering, and control of weeds, pests, and diseases).

**Hedges/Living Fences**

Hedges and living fences are useful in areas with medium to high population density and where animals roam freely in the area. Live fences or hedges provide an alternative to constructed fencing for:

- The demarcation of boundaries; for example between/around schools, farms, and fields (particularly paddocks in grazing schemes)
- Protection from the ravages of free-grazing livestock; for example crop lands, orchards, nurseries, woodlots, dams, protein banks (grazing schemes), vegetable gardens, and homes

In addition hedges can offer secondary benefits, such as reducing the adverse influence of wind and can provide not only organic material to adjacent soils but also multiple tree products (firewood, poles, fruit, fibre, medicine, etc.) to the local community. The appropriate farming system for living fences is the small to medium sized farm with permanent crop cultivation.

**Mixed Intercropping**

Mixed intercropping is most useful in poor or easily depleted soils, on flat to gently sloping land, in areas of medium population density. This system will serve to restore/improve soil nutrients and increase organic materials.

The appropriate farming system here is permanent crop cultivation, medium to small farm size using medium labor input per unit of land, and no animal cultivation (at high tree densities).

**Multistory Planting of Domestic/Industrial Tree Crops**

Multistory tree crops are best suited to home gardens and the upper story of productive trees in hedges or plantations. Multistory planting fits well in
areas with high population density and high rainfall. It contributes resources for tree products, some of which supply household requirements. This may also reduce cash expenditures and add to cash income. Multistory tree crops are appropriate for small sized farms with high labor input per unit of area.

**Tree Planting Around Watering Places and Dams**

Tree planting around watering places and dams is appropriate where there is a high population density or presence of animals in the area. Planting trees will reduce the damage to water sources and dams that is caused by livestock. It will also provide materials for wood products for home consumption or sale. Trees can be laid out in strips or planted in woodlots. A mixture of trees and grasses is helpful. Planting can also be spaced and mixed with multistory species. The appropriate farm system is a small to medium sized farm with permanent crop cultivation.

**Selective Clearing**

Selective clearing is useful in areas with substantial acreage of native woodlands. It is particularly useful in resettlement areas where there is a low population density. Selective clearing will conserve functional indigenous vegetation and biodiversity and help to ensure future supplies of woodland products and germ plasm. In this system selected trees are left in croplands. Strips of trees and shrubs are left around newly opened plots, between fields and along roads, tracks, and watercourses. The appropriate farm system is the medium to large farm with low labor input per unit area.

**Woodlot Planting for Fuelwood and Poles**

Woodlot planting for fuelwood and poles is appropriate for deforested areas and for all areas with a market for poles and/or firewood. Such woodlots can produce fuelwood/poles to meet household and/or household industry requirements. They may also add to the cash flow of the family. Woodlots should be fenced. Where possible "live fences" should be established within the protection offered by the fence. Firebreaks are recommended. The appropriate farm system is the medium to large farm with low to medium labor input per unit area. The system is also appropriate for tobacco farms (for barn construction as well as curing) and small industries such as brick works or small mines.
PART FOUR

Ecological Management of Insect Pests, Pathogens, and Weeds
Integrated Pest Management

The IPM movement arose in the early 1970s in response to concerns about impacts of pesticides on the environment. By providing an alternative to the strategy of unilateral intervention with chemicals, IPM changed the philosophy of crop protection to one that entailed a deeper understanding of insect and crop ecology and relied on the use of several complementary tactics. It was envisioned that ecological theory should provide a basis for predicting how specific changes in production practices and inputs might effect pest problems. It was thought that ecology could also aid in the design of agricultural systems less vulnerable to pest outbreaks (Kogan 1986). Thus, IPM can be defined as a pest management strategy where, in the socio-economic context of farming systems, the associated environment and the population dynamics of the species utilizes all suitable and compatible techniques and methods to maintain a pest population below the economic injury level (Dent 1991).

In theory, integrated pest management should incorporate several diverse tactics of pest control, relying first on natural control factors (pathogens, parasites, predators, and weather, for example) and management using pesticides as a last resource. It relies on pest population dynamics, such as length of immature stage or reproductive period, to suggest exploitable weaknesses in the biology of the pest. Another large part of IPM involves determining the economic thresholds of yield and refraining from insect control below these thresholds. IPM practitioners evaluate whether there will be sufficient pests to justify control by the grower, whether the pests will last long enough or remain dense enough to lower yields, and whether natural controls will intervene. The actions taken may be cultural methods, biological controls, the use of toxic chemicals, or a combination of these.
Cultural methods include manipulation of the density and diversity of vegetation, cultivation, sanitation, variation in planting and harvesting dates and the varieties planted, and alteration of fertility or irrigation levels. Biological control relies on the use of predators, parasites, pathogens, and nematodes and may involve foreign exploration to find natural enemies, the mass release of enemies, and the conservation of natural enemies. Transition from theory to practice, however, has been disappointing.

Some pest management programs have been unjustifiably slow in putting ecologically based theory into practice. The lack of training in "holistic thinking," the sense of short-range urgency in applied "practical" research, and the "need" to defend a particular discipline from intrusion of "others" can all inhibit the integration of theory and application.

Unfortunately, pest control research has been too subservient to pressure groups in the legislature, large farmer associations, and, particularly, the pesticide industry. Since biological methods of pest suppression do not lend themselves readily to agribusiness systems for large-scale manufacturing and marketing as do conventional pesticides, it is evidence that private enterprises are reluctant to incur the expense of their development. As a concept, IPM has been incorporated into large-scale farming to reduce the costs of pest control. Although pesticide applications have become fewer and more efficient, the use of toxic substances is still maintained. Hence, IPM, in most cases, signifies integrated pesticide management emphasizing pest monitoring, regulated insecticide use, and planting of resistant crop varieties, and, as such, has not been able to challenge the fundamental industrial structure of modern agriculture (Soule and Piper 1992).

Furthermore, in some cases, bio-environmental strategies in crop protection involve yield stabilization rather than maximization. In ecologically managed systems, productivity on a crop-unit basis might be reduced, but other desirable environmental features, such as the multiple-use capacity of the habitat, are enhanced. The net result appears to be greater resource diversity and overall biological stability, though it could be argued that these advantages are not substantial and tangible enough to be justified from the commodity yield point of view. Nevertheless, energy shortages, environmental degradation, and economic inflation increasingly show that short-term financial gain should no longer be the primary driving force in agriculture. Slowly, energy conservation, environmental quality, and sustainability will assume such a role.

Integrated pest management should be oriented to prevent out-breaks by improving the stability of the crop systems rather than coping with pest problems after they occur. Currently, the issue in pest management is to design systems that suppress a complex of pests while achieving maximum yield and quality and minimum environmental damage. These objectives may appear to conflict, and when yield and market quality are overemphasized,
they usually do. However, the conflict can be avoided when IPM systems are coordinated with more broadly related systems of land and water, resource conservation, environmental protection, and socioeconomic development. IPM systems should be designed to balance pests and beneficial organisms based on known economic, social, and ecological consequences.

An equilibrium of the crop fauna can be established by organizing vegetational diversity within and around the target crop fields. Providing the right kind of plant diversity throughout the year and manipulating time of planting, size of fields, and species composition of crop field borders can make habitats and food resources continually available for populations of beneficial arthropods and make habitats less favorable for pests.

**Cultural Control of Insect Pests**

Cultural control of insect pests is effected by the manipulation of the environment in such a way as to render it unfavorable to the pest, or alternatively, optimal for natural enemy action. This is achieved through the use of a variety of techniques such as rotation, temporal manipulation of crop sowing and spraying, and other biodiversity-enhancing techniques such as intercropping and management of weeds and field margins. The objectives are first to reduce the initial colonization of the pest, and should colonization be achieved, to reduce the reproduction, survival, and dispersal of the pest (Dent 1991).

Crop rotation, tillage and planting date are three agronomic practices that can directly affect crop yield as well as the level of insect pest infestation within a crop. Generally, crop rotation is most effective against pest species that have a narrow host range and limited range of dispersal. It is more difficult to devise rotations against polyphagous and/or mobile pests. A new generation of an insect pest that may have overwintered in the vicinity of its host crop will be faced with a different, non-host crop plant in a subsequent season. The insect pest will be obliged to disperse, and, for insects with poor dispersive powers, this could reduce the likelihood of finding a host with the result that colonization of some fields of the host crop species may subsequently be retarded. Rotations such as potato-wheat have been shown to be effective against the Colorado potato beetle (*Leptinotarsa decemlineata*) by creating a delay in the time of crop infestation. In Europe, typical rotations involve grasses, legumes, and root crops, which have been used to control wireworms (*Agriotes* spp.), chafers (*Melolontha melolontha* and *Amphimallon solstitialis*), and leatherjackets (*Tipula* spp.) (Burn *et. al* 1987).

The type of cultivation or tillage can markedly influence the soil environment and affect insect survival either indirectly by creating inhospitable conditions and by exposing the insects to their natural enemies or directly by physical damage inflicted during the actual tillage process (Stinner and
House 1990). Cultivation is known to affect the numbers of eggs and nymphs of two grasshopper pests, *Kraussaria angulifera* and *Oedaleus senegalensis*, by exposing the egg pods to desiccation, by reducing the level of food, shelter, and vegetation available, and by making the soil rough and unsuitable for egg laying.

Emergence of the sunflower seed weevil (*Smicronyx fulvus*) was reduced by 29-56% with the use of a mould-board plough, which turns over the soil, effectively burying the late larval and pupal stages. However, this covering effect was thought to be only partially responsible for the increased mortality as a chisel plough resulted in a reduced emergence of between 36 and 39% without moving the larvae substantially deeper in the soil profile. Thus, it was concluded that factors such as aeration, soil temperature and drying, and physical damage resulting from tillage were also important factors (Dent 1991).

In many regions, early sown crops may benefit from a reduced insect pest infestation. Varying the planting time of crops works as a means of cultural control by creating asynchrony between crop phenology and the insect pest's phenology, which can retard the rate of colonization or mean that the pest fails to coincide with a critical crop growth stage. For such methods to have a major impact though, planting times need to be synchronized between farms within a region to reduce the variation in available crop stages. In Ethiopia, maize sown in April and early May had significantly lower infestations of first generation larvae while levels of infestation by second generation larvae were significantly higher on later sowing lots, negatively impacting maize yields (Dent 1991).

In general, increase in plant density, that is, a reduction in plant spacing, seems to reduce pest numbers. One of the main reasons for the response of insects to varying plant density has been the contrast between plants and their soil background and the effect of this on the optomotor landing response of the flying insects. *Aphis craccivora*, *Aphis gossypii*, and *Longiunguis sacchari* were trapped at approximately 1 m above ground more often over widely spaced than over closely spaced groundnuts. At crop height, *A. craccivora* and *A. gossypii* showed a similar but even greater response to plant spacing. This effect was attributed to an optomotor response to the contrast between bare earth and the plants and hence the stimulus was greater over the wider spaced plants.

Other reasons given to explain lower insect numbers in dense plantings are host plant condition (Farrell 1984), excess vegetation acting as a deterrent (Delobel 1981), changes in the microenvironment in favor of the pest and its natural enemies, and the crop attractiveness (Brom et. al 1987).
Vegetational Diversity and Pest Problems

Most entomologists, plant pathologists, and weed scientists agree that the intensification that has accompanied the growth of agriculture has promoted several practices that favor insect pests, weeds, and diseases. These include (Zadoks and Schein 1979, Pimentel and Goodman 1978):

- Enlargement of fields, resulting in extensive monocultures or short rotational patterns of low species diversity
- Aggregation of fields of similar species and/or varieties, decreasing mosaic diversity at the regional level
- Increase in the density of host crop plants by adopting crop spacings that encourage pest outbreaks and epidemics
- Increase in the uniformity of host populations, thereby decreasing genetic diversity. Genetic alteration of crops to increase yield with little attention to the reduction of factors regulating natural resistance to insects and pathogens

Plant pathologists recognize the following patterns of disease behavior in monocultures (Zadoks and Schein 1979):

1. Disease increases to maximum intensity and severity, remaining for the duration of the monoculture.
2. Disease increases to a limited extent with moderate intensity, maintained at a plateau.
3. Disease shows minimal or undetectable development throughout the monoculture.
4. Disease exhibits a variable intensity of development, in erratic cycles.
5. Disease increases to a peak of maximum intensity followed by a period of declining severity.

With insects, these patterns have not been clearly defined. However, the analyses of Andow (1983) and Altieri and Letourneau (1982) indicate that insect pest abundance often increases with extended periods of monoculture, destruction of woodlands and hedgerows, disproportionate increases in crop acreage, replacement of diversified farming or low-maintenance crops, and replacement of natural forests by annual crops. Andow (1983) mentions four examples (two in cotton and two in wheat) in which increasing monocultures eliminated alternative host plants, so large populations of multivoltine, polyphagous herbivores (e.g., *Heliothis zea*, *Bemisia tabaci*, and *Oscinella* spp.) were unable to build up. Present evidence supports Andow's hypothesis,
that monophagous, less agile pests are good candidates for outbreaks depending upon increasing monoculture. Other agricultural practices such as fertilization, irrigation, and pesticide applications can make plants more or less susceptible to pest and disease attack.

Researchers searching for an ecological approach to pest control envision the restoration of plant diversity in agriculture. They hope that by adding selective diversity to crop systems, it will be possible to capture for agroecosystems some of the stable properties of natural communities (Root 1973). Several researchers have explored the effects of increased diversity on pest management (Litsinger and Moody 1976, Perrin 1977, Cromartie 1981, Altieri and Letourneau 1982).

**Monocultures in the United States**

Monocultures have increased dramatically in the United States both spatially, in that the land devoted to single crops has expanded within a geographic area, and temporally, through the year-to-year production of the same species on the same land. Although using present information it is difficult to quantify the extent of monocultures, a task force on spatial heterogeneity in agricultural landscapes reported that crop diversity per unit of arable land has decreased and croplands have become increasingly concentrated (USDA 1973). These trends are particularly evident in the corn belt, Mississippi delta, Red River valley, Texas high plains, California irrigation areas, southern Florida, and the Kansas/Oklahoma winter wheat belt.

The state of Illinois was the subject of a pilot analysis of trends in agricultural diversity for over 32 years (USDA 1973). Studying corn, soybeans, wheat, oats, hay, and plowland pasture, USDA scientists applied the Shannon-Weaver index to nine crop districts for year-to-year comparisons of diversity. In seven districts, the diversity fell precipitously beginning in the mid-1950s. Specialization of corn and soybean production (not the diverse species assemblages that make up hay or pastureland) accounted for the increase in monoculture and aggregation of croplands in most of the studied districts.

Political and economic forces usually influence the trend to devote large areas to monoculture. Concentration of directed research on particular commodities increases production technology and profitability for certain commodities, thus contributing to monoculture. Capital-intensive, directed agricultural research products tend to be large-scale and to benefit large monoculture farmers. Also, because of economies of scale, the concentration of managerial expertise, mechanization and marketing all support the trend toward monoculture practices (Buttel 1980b).
Diversity and Insect Populations

Ecological Theory

Exposed fields and concentrations of a single-crop species open the way for pest infestations by providing concentrated resources and uniform physical conditions that encourage insect invasions (Root 1973). The abundance and effectiveness of predators are reduced because these simplified environments provide inadequate alternative sources of food, shelter, breeding sites, and other environmental factors (van den Bosch and Telford 1964). Herbivorous insect pests are more likely to colonize and remain longer on crop hosts that are concentrated because the entire life requirements of the pests are met in these simple environments (Root 1973). As a result, populations of specialized pests attain economically undesirable levels.

Two hypotheses explain pest reduction in polycultures (Root 1973, Altieri et al. 1978, Bach 1980, Risch 1983, Altieri and Liebman 1986 and 1988). The first, the natural enemies hypothesis, predicts greater mortality of specialist and generalist insect pests in polycultures because of greater numbers of insect predators and parasites. Greater numbers of these natural enemies result because of the better conditions for their survival. Compared with monocultures, polycultures can provide more pollen and nectar sources (which can attract natural enemies and increase their reproductive potential), increased ground cover (which favors certain predators like carabid beetles), and increased diversity of herbivorous insects (which can serve as alternative food sources for natural enemies and make them less likely to leave when the main pest species are rare).

The second hypothesis, the resource concentration hypothesis, predicts that specialized insect pests will be less abundant in polycultures when the mixtures are composed of host and non-host crops. Specialist pests will have a more difficult time locating, remaining on, and reproducing on their preferred hosts when these plants are more dispersed spatially and masked by the confusing visual and chemical stimuli presented by associated non-host crops. Some of the possible mechanisms suggested by both hypotheses that explain lower insect pest populations in multiple cropping systems are given in Table 13.1.

Agroecosystem Diversification and Biological Pest Control

Crop monocultures are difficult environments in which to induce efficient biological pest control because these systems lack adequate resources for effective performance of natural enemies and because of the disturbing cultural practices often utilized in such systems. More diversified cropping
TABLE 13.1 Possible effects of intercropping on insect pest population (after Altieri and Liebman 1986).

**Interference with host-seeking behavior**

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Camouflage</td>
<td>A host plant may be protected from insect pests by the physical presence of other overlapping plants (i.e., camouflage of bean seedlings by standing rice stubble for beanfly).</td>
</tr>
<tr>
<td>b. Crop background</td>
<td>Certain pests prefer a crop background of a particular color and/or texture (i.e., aphids, flea beetle, and Pieris rapae are more attracted to cole crops with a background of bare soil than to ones with a weedy background).</td>
</tr>
<tr>
<td>c. Masking or dilution of attractant stimuli</td>
<td>Presence of non-host plants can mask or dilute the attractant stimuli of host plants leading to a breakdown of orientation, feeding, and reproduction processes (i.e., Phyllotreta cruciferae in collards).</td>
</tr>
<tr>
<td>d. Repellent chemical stimuli</td>
<td>Aromatic odors of certain plants can disrupt host finding behavior (i.e., grass borders repel leafhoppers in beans, populations of Plutella xylostella are repelled from cabbage/tomato intercrops).</td>
</tr>
</tbody>
</table>

**Interference with population development and survival**

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Mechanical barriers</td>
<td>All companion crops may block the dispersal of herbivores across the polyculture. Restricted dispersal may also result from mixing resistant and susceptible cultivars of one crop by settling on non-host components.</td>
</tr>
<tr>
<td>b. Lack of arrestant stimuli</td>
<td>The presence of different host and non-host plants in a field may affect colonization of herbivores. If an herbivore descends on a non-host it may leave the plot quicker than if it descends on a host plant.</td>
</tr>
<tr>
<td>c. Microclimate influences</td>
<td>In an intercropping system favorable aspects of microclimate conditions are highly fractioned, therefore insects may experience difficulty in locating and remaining in suitable microhabitats. Shade derived from denser canopies may affect feeding of certain insects and/or increase relative humidity, which may favor entomophagous fungi.</td>
</tr>
<tr>
<td>d. Biotic influences</td>
<td>Crop mixtures may enhance natural enemy complexes.</td>
</tr>
</tbody>
</table>
systems already contain certain specific resources for natural enemies provided by plant diversity, especially when not disturbed with pesticides (Altieri and Letourneau 1982). Thus, by replacing or adding diversity to existing systems, it may be possible to exert changes in habitat diversity that enhance natural enemy abundance and effectiveness by (van den Bosch and Telford 1964, Powell 1986):

1. Providing alternative hosts/prey at time of pest host scarcity
2. Providing food (pollen and nectar) for adult parasitoids and predators
3. Providing refuges for overwintering, nesting, and so forth
4. Maintaining acceptable pest populations over extended periods to ensure continued survival of beneficial insects

The specific resulting effect on the strategy to use will depend on the species of herbivores and associated natural enemies as well as on properties of the vegetation, the physiological condition of the crop, or the nature of the direct effects of particular plant species (Letourneau 1987). In addition, the success of enhancement measures can be influenced by the scale upon which they are implemented (i.e., field scale, farming unit, or region) since field size, within-field and surrounding vegetation composition, and the level of field isolation (i.e., distance from source of colonizers) will all affect immigration rates, emigration rates, and the effective tenure time of a particular natural enemy in a crop field.

Perhaps one of the best strategies to increase effectiveness of predators and parasitoids is the manipulation of nontarget food resources (i.e., alternate hosts-prey and pollen-nectar) (Rabb et al. 1976). Here it is not only important that the density of the nontarget resource be high to influence enemy populations, but that the spatial distribution and temporal dispersion of the resource be also adequate. Proper manipulation of the nontarget resource should result in the enemies colonizing the habitat earlier in the season than the pest and frequently encountering an evenly distributed resource in the field, thus increasing the probability of the enemy to remain in the habitat and reproduce (Andow and Risch 1985). Certain polycultural arrangements increase and others reduce the spatial heterogeneity of specific food resources; thus particular species of natural enemies may be more or less abundant in a specific polyculture. These effects and responses can only be determined experimentally across a whole range of agroecosystems. The task is indeed overwhelming since enhancement techniques must necessarily be site-specific.

The literature is full of examples of experiments documenting that diversification of cropping systems often leads to reduced herbivore populations. The studies suggest that the more diverse the agroecosystem and the longer this diversity remains undisturbed, the more internal links develop
to promote greater insect stability. It is clear, however, that the stability of the insect community depends not only on its trophic diversity, but on the actual density-dependence nature of the trophic levels (Southwood and Way 1970). In other words, stability will depend on the precision of the response of any particular trophic link to an increase in the population from a lower level.

Although most experiments have documented insect population trends in single versus complex crop habitats, a few have concentrated on elucidating the nature and dynamics of the trophic relationships between plants-herbivores and natural enemies in diversified agroecosystems. Several lines of studies have developed:

**Crop-Weed-Insect Interaction Studies.** Evidence indicates that weeds influence the diversity and abundance of insect herbivores and associated natural enemies in crop systems. Certain weeds (mostly Umbelliferae, Leguminosae, and Compositae) play an important ecological role by harboring and supporting a complex of beneficial arthropods that aid in suppressing pest populations (Altieri et al. 1977, Altieri and Whitcomb 1979). Specific examples of crop-weed associations that enhance biocontrol are provided in Chapter 14.

**Insect Dynamics in Annual Polycultures.** Overwhelming evidence suggests that polycultures support a lower herbivore load than monocultures. One factor explaining this trend is that relatively more stable natural enemy populations can persist in polycultures due to the more continuous availability of food sources and microhabitats (Risch 1981, Helenius 1989). The other possibility is that specialized herbivores are more likely to find and remain on pure crop stands, which provide concentrated resources and monotonous physical conditions (Root 1973). Specific examples of insect suppressant polycultures are provided in Table 13.2.

Reductions in pest populations because of the use of polycultures can have dramatic effects on crop yields (Table 13.3). For example, competition from cowpea reduced cassava yield in polyculture when cassava whiteflies were controlled with insecticides. However, when no insecticides were used for whitefly control, yield of cassava in polyculture was higher than in monoculture. Without insecticides, the competitive effect of cowpea was more than offset by the protection is provided to the cassava (Gold 1987).

**Herbivores in Complex Perennial Crop Systems.** Most of these studies have explored the effects of the manipulation of ground cover vegetation on insect pests and associated enemies. The data indicates that orchards with rich floral undergrowth exhibit a lower incidence of insect pests than clean cultivated orchards, mainly because of an increased abundance and efficiency of predators and parasitoids (Altieri and Schmidt 1985). In some cases, ground cover directly affects herbivore species which discriminate among trees with and without cover beneath.
<table>
<thead>
<tr>
<th>Multiple cropping system</th>
<th>Pest(s) regulated</th>
<th>Factor(s) involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beans grown in relay intercropping with winter wheat</td>
<td>Empoasca fabae and Aphis fabae</td>
<td>Impairment of visual searching behavior of dispersing aphids</td>
</tr>
<tr>
<td>Brassica crops and beans</td>
<td>Brevicoryne brassicae and Delia brassicae</td>
<td>Higher predation and disruption of oviposition behavior</td>
</tr>
<tr>
<td>Brussels sprouts intercropped with fava beans and/or mustard</td>
<td>Flea beetle, Phyllotreta cruciferae, and cabbage aphis Brevicoryne brassicae</td>
<td>Reduced plant apparency trap cropping, enhanced biological control</td>
</tr>
<tr>
<td>Cabbage intercropped with white and red clover</td>
<td>Erioischia brassicae, cabbage aphids, and imported cabbage butterfly (Pieris rapae)</td>
<td>Interference with colonization and increase of ground beetles</td>
</tr>
<tr>
<td>Intercropping of Cajanus cajan with red, black, and green gram</td>
<td>Podborers, jassids, and membracids</td>
<td>Delayed colonization of herbivores</td>
</tr>
<tr>
<td>Cassava intercropped with cowpeas</td>
<td>Whiteflies, Aleurotrachelus socialis, and Trialeurodes variabilis</td>
<td>Changes in plant vigor and increased abundance of natural enemies</td>
</tr>
<tr>
<td>Cauliflower strip-cropped with rape and/or marigold</td>
<td>Blossom beetle (Meligethes aeneus)</td>
<td>Trap cropping</td>
</tr>
<tr>
<td>Corn intercropped with beans</td>
<td>Leafhoppers (Empoasca kraemeri), leaf beetle (Diabrotica balleata), and fall armyworm (Spodoptera frugiperda)</td>
<td>Increase in beneficial insects and interference with colonization</td>
</tr>
<tr>
<td>Corn intercropped with fava beans and squash</td>
<td>Aphids, Tetanychus urticae, and Macrodactylus sp.</td>
<td>Enhanced abundance of predators</td>
</tr>
<tr>
<td>Corn intercropped with clover</td>
<td>Ostrinia nubilalis</td>
<td>?</td>
</tr>
<tr>
<td>Corn intercropped with soybean</td>
<td>European corn borer (Ostrinia nubilalis)</td>
<td>Differences in corn varietal resistance</td>
</tr>
<tr>
<td>Corn intercropped with sweet potatoes</td>
<td>Leaf beetles (Diabrotica spp.) and leafhoppers (Agallia lingula)</td>
<td>Increase in parasitic wasps</td>
</tr>
<tr>
<td>Intercropping corn and beans</td>
<td>Dalbulus maidis</td>
<td>Interference with leafhopper movement</td>
</tr>
<tr>
<td>Cotton intercropped with forage cowpea</td>
<td>Boll weevil (Anthonomus grandis)</td>
<td>Population increase of parasitic wasps (Eurytoma sp.)</td>
</tr>
<tr>
<td>Intercropping cotton with sorghum or maize</td>
<td>Corn earworm (Heliothis zea)</td>
<td>Increased abundance of predators</td>
</tr>
<tr>
<td>Cotton intercropped with okra</td>
<td>Podagricta sp.</td>
<td>Trap cropping</td>
</tr>
<tr>
<td>Multiple cropping system</td>
<td>Pest(s) regulated</td>
<td>Factor(s) involved</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Strip cropping of cotton and alfalfa</td>
<td>Plant bugs (<em>Lygus hesperus</em> and <em>L. elisus</em>)</td>
<td>Prevention of emigration and synchrony in the relationship between pests and natural enemies</td>
</tr>
<tr>
<td>Strip cropping of cotton and alfalfa on one side and maize and soybean on the other</td>
<td>Corn earworm (<em>Heliothis zea</em>) and cabbage looper (<em>Trichoplusia ni</em>)</td>
<td>Increased abundance of predators</td>
</tr>
<tr>
<td>Intercropping cowpea and sorghum</td>
<td>Leaf beetle (<em>Oethca bennigseni</em>)</td>
<td>Interference of air currents</td>
</tr>
<tr>
<td>Cucumbers intercropped with maize and broccoli</td>
<td><em>Acalymma vittatum</em></td>
<td>Interference with movement and tenure time on host plants</td>
</tr>
<tr>
<td>Groundnuts intercropped with field beans</td>
<td><em>Aphis craccivora</em></td>
<td>Aphids trapped on epidermal hairs of beans</td>
</tr>
<tr>
<td>Maize intercropped with canavalia</td>
<td><em>Prorachia daria</em> and fall armyworm (<em>Spodoptera frugiperda</em>)</td>
<td>Not reported</td>
</tr>
<tr>
<td>Maize-bean intercropping</td>
<td><em>Spodoptera frugiperda</em> and <em>Diatraea lineolata</em></td>
<td>Lower oviposition rates, trap cropping</td>
</tr>
<tr>
<td>Strip cropping of muskmelons with wheat</td>
<td><em>Myzus persicae</em></td>
<td>Interference with aphid dispersal</td>
</tr>
<tr>
<td>Oats intercropped with field beans</td>
<td><em>Rhopalosiphum padi</em></td>
<td>Interference with secondary dispersal after alighting on the crop</td>
</tr>
<tr>
<td>Peaches intercropped with strawberries</td>
<td>Strawberry leafroller (<em>Ancylis comptana</em>) and Oriental fruit moth (<em>Grapholita molesta</em>)</td>
<td>Population increase of parasites (<em>Macrocentrus ancylovora</em>, <em>Microbracon gelechiae</em>, and <em>Lixophaga variabilis</em>)</td>
</tr>
<tr>
<td>Peanut intercropped with maize</td>
<td>Corn borer (<em>Ostrinia furnacalis</em>)</td>
<td>Abundance of spider (<em>Lycosa</em> sp.)</td>
</tr>
<tr>
<td>Sesame intercropped with corn or sorghum</td>
<td>Webworms (<em>Antigostra</em> sp.)</td>
<td>Shading by the taller companion crop</td>
</tr>
<tr>
<td>Sesame intercropped with cotton</td>
<td><em>Heliothus</em> spp.</td>
<td>Increase of beneficial insects and trap cropping</td>
</tr>
<tr>
<td>Soybean strip cropped with snap beans</td>
<td><em>Epilachna varivestis</em></td>
<td>Trap cropping</td>
</tr>
<tr>
<td>Squash intercropped with maize</td>
<td><em>Acalymma thieimi</em> and <em>Diabrotica balleata</em></td>
<td>Increased dispersion due to avoidance of host plants shaded by maize and interference with flight movements by maize stalks</td>
</tr>
<tr>
<td>Tomato and tobacco intercropped with cabbage</td>
<td>Flea beetles (<em>Phyllostreta cruciferia</em>)</td>
<td>Feeding inhibition by odors from non-host plants</td>
</tr>
<tr>
<td>Tomato intercropped with cabbage</td>
<td>Diamondback moth (<em>Plutella xylostella</em>)</td>
<td>Chemical repellency or masking</td>
</tr>
</tbody>
</table>
TABLE 13.3 Commercial root yield of cassava in monoculture and in polyculture with cowpea, with and without insecticide applications. Cassava grew at the same density in all four treatments. The experiments were conducted at Nataima, Colombia (Gold 1987).

<table>
<thead>
<tr>
<th>Insecticides</th>
<th>In Monoculture</th>
<th>In Polyculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>applied</td>
<td>1.91</td>
<td>1.31</td>
</tr>
<tr>
<td>not applied</td>
<td>0.80</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Diversity and Plant Diseases

Monocultures are almost invariably prone to disease. One of the epidemiological strategies for minimizing losses from plant diseases and nematodes is to increase the species and/or genetic diversity of cropping systems. Larios (1976) documented evidence of disease buffering in various tropical intercropping schemes. Cowpea intercropped with corn showed less inoculum liberation and dissemination than in cowpea monocultures. The onset of mildew (*Oidium manihotis*) and scab (*Sphaceloma* sp.) infestation was delayed on cassava associated with beans and/or sweet potatoes. Cowpea mosaic virus and cowpea chlorotic virus occurred at lower levels in the cowpea intercropped with cassava or plantain.

The use of non-host crops in interplantings can significantly reduce the rate of virus spread. A buffer crop such as maize, when grown between the source of peanut mottle and a susceptible soybean crop, can reduce the amount of separation required to prevent disease spread. Mosaic virus of alfalfa is more prevalent in monocultures than in mixtures with cocksfoot grass. Growing mustard or barley, which grow to heights of 66 and 41 cm, respectively, together with sugar beet stecklings, lowers the incidence of beet mild yellowing virus in sugar beets (Altieri and Liebman 1986). The available examples indicate that mixtures of crop species or varieties (multilines) buffer against disease losses by delaying the onset of the disease, reducing spore dissemination or modifying microenvironmental conditions such as humidity, light, temperature, and air movement (Browning and Frey 1969, Larios 1976).

Certain associated plants function as repellents, antifeedants, growth disrupters, or toxicants. In the case of soil-borne pathogens, some plant combinations and organic amendments enhance soil fungistasis and antibiotic through indirect effects on soil organic matter (Sumner et al. 1981).
Diversity and Nematodes

A strategy based on diversity is the use of trap crops, which are host crops sown to attract nematodes but destined to be harvested or destroyed before the nematodes hatch. This tactic has been advocated for cyst nematodes, by sowing crucifers to be plowed in before the nematodes of beets can develop fully. The same objective is achieved in pineapple (*Ananas comosus*) plantations by planting tomatoes and destroying them before root-knot nematodes can produce eggs (Palti 1981).

There is also evidence that some plants adversely affect nematode populations through toxic action. Oostenbrink et al. (1957) showed that several varieties of *Tagetes erecta* and *T. patula* reduced the population of certain root-infecting nematode species such as *Pratylenchus*, *Tylenchorchynchus*, and *Rotylenchus*. The effect of marigolds on *Pratylenchus* eelworms appears to be due to the nematicidal action of the growing plant roots, which exude alpha-terthienyl. In subsequent studies, Visser and Vythilingum (1959) also reported that these two marigold species considerably decreased *Pratylenchus coffeae* and *Meloidogyne javanica* populations in tea (*Camellia sinensis*) soil. Cultivating marigolds reduced nematodes more quickly and more effectively than keeping the tea soil fallow. There are other plants whose root extracts show nematicidal action. For example, *Ambrosia* spp. and *Iva xanthifolia* reduce populations of *P. penetrans*.

Little work has been conducted on nematode suppression in intercropping systems. The nematode *Anguina tritici*, which enters wheat seedlings from the soil and infests the ears, has been partially controlled in India by growing *Polygonum hydropiper* with wheat (*Triticum* sp.). Also in India, the plant *Sesamum orientale* has been found to produce root exudates that are nematicidal to rootknot nematodes and to decrease rootknot infestation in *Abelmoschus esculentus* growing alongside (Altieri and Liebman 1986).

Egunjobi (1984) studied the ecology of *P. brachyurus* in traditional maize cropping systems of Nigeria. NPK fertilizer applications increased the numbers of the nematode more in soil under monoculture maize than in plots with maize intercropped with cowpea, groundnut, or green gram.

Diversity and Weed Populations

The continuous manipulations of the fields necessary for modern crop production have favored the selection of opportunistic and competitive weeds because most weed species are stimulated by regular disturbances in monocultures. Of the factors that influence the crop/weed balance in a field, the density of crop plants and weeds plays a major role in the outcome of
competition. When the cropping pattern is intensive, the level and type of weed community is a product of the crop and its management. In multiple cropping systems, the nature of the crop mixtures (especially canopy closure) can keep the soil covered throughout the growing season, shading out sensitive weed species and minimizing the need for weed control. Intercropping systems of corn/mung bean and corn/sweet potato are common systems that inhibit weed competition. In these systems, the complex canopies with large leaf areas intercept a significant proportion of the incident light, shading out sensitive weed species (Bantilan et al. 1974).

In general, weed suppression in intercropping systems depends on the density, relative proportions and spatial arrangement of the component crops, and on the soil fertility. Mechanisms explaining overyielding and weed suppression in polycultures have been limited to resource and niche preemption, competitive exclusion, and allelochemical interference (Altieri and Liebman 1988).

Allelopathy may contribute to increasing the competitiveness of crops over co-existing weeds in monocultures and polycultures. Crops such as rye, barley, wheat, tobacco, and oats release toxic substances into the environment, either through root exudation or from decaying plant material, that inhibit the germination and growth of some weed species. Plant leachates from certain varieties of cucumbers have allelopathic effects on prosomillet. Root secretions from rye and oat accessions can inhibit germination and growth of weeds such as wild mustard, *Brassica* spp. and poppy (*Papaver rhoeas*) (Putnam and Duke 1978). The potential role of allelopathy in weed management is further discussed in Chapter 14.
Weed Ecology and Management

Agriculture has had a major influence on the evolution of weeds. Agricultural activities have kept plant community succession in its early stages. The major vegetational components of these communities are what modern agriculture terms "weeds." Thus far, about 250 plant species are sufficiently troublesome to be universally called weeds. Many of these weeds were introduced from distant geographic areas or are native "opportunists" favored by particular human disturbances. Crop monocultures seldom use all of the moisture, nutrients, and light available to plant growth, thereby leaving ecological niches that must be protected against invasion and competition from opportunistic weeds.

Most studies of weed ecology have emphasized the growth characteristics and adaptations that enable weeds to exploit the ecological niches left open in croplands, and the adaptive mechanisms that enable weeds to survive under conditions of maximum soil disturbance, such as conventional tillage systems. These studies have shown that the characteristics that enable weeds to successfully colonize agroecosystems include (Baker 1974):

1. Germination requirements fulfilled: Cultivation enhances seed germination of many weed species because it augments the number of microsites (a soil location with the right germination conditions).
2. Discontinuous germination and marked periodicity of germination: Most species germinate best at certain periods in the year. For example, *Avena fatua* germinates best in spring and fall, and *Chenopodium album* in late spring and early fall.
3. Longevity of seeds: Seeds of *Oenothera biennis*, *Verbascum blattaria*, and *Rumex crispus* can remain viable even after 80 years.
4. Variable seed dormancy.
5. Rapid growth through vegetative phase to flowering.
6. High output of seeds under favorable conditions: For example, *Amaranthus retroflexus* can produce up to 110,000 seeds per plant.
7. Ability to produce seeds for as long as growing conditions permit: Seed production often begins after a short period of vegetative growth.
8. Self-compatible but not completely autogamous or apomictic: Many annual weeds can set seed without external pollinators.
9. Adapted to cross-pollination by unspecialized visitors or wind.
10. Adapted to short- and long-distance dispersal.
11. Perennials have vigorous vegetative reproduction or regeneration from fragments (rhizomes, dormant buds, bulbs, taproots, etc.).
12. Ability to compete interspecifically by special means (rosette, choking growth, allelochemicals).
13. Ability to adapt to and tolerate variable environments.

**Crop/Weed Competition**

Crop/weed interactions vary among different geographic regions, among different crops and even among the same crops in different situations. In fact, crop/weed interactions are overwhelmingly site-specific and season-specific. They vary according to plant species involved, density, management practices, and environmental factors (Radosevich and Holt 1984). Thus, worldwide figures on crop losses may be irrelevant. However, generalizations about crop yield losses due to weeds have justified the promotion of season-long, weed-free crop systems that rely on costly chemical herbicides. This reliance has been sustained partly by chemical companies' claims that replacing herbicides with nonchemical weed control would reduce farm revenues 31 percent and result in economic losses of $13 billion (Aldrich 1984).

The end result of weed competition is a reduction in the yield or quality of the crop. In many crops, weeds left uncontrolled for the season usually prevent the production of any marketable produce. However, the outcome of this competition is affected by several factors (Figure 14.1, Zimdahl 1980):

1. Period of weed growth in relation to crop emergence: Weed competition during the first third or so of the crop cycle tends to have the greatest effect on crop yields. Generally, crop yield increases little when crops are weeded after this critical period of weed competition (Kasasian and Seeyave 1969). This period represents the time interval between two separately measured components: the maximum weed-infested period, or the length of time that weeds that emerge with the crop can remain before they begin to interfere with crop growth; and the minimum weed-free period, or the length of time a crop must be free of weeds after planting in order to prevent
FIGURE 14.1 Factors affecting weed-crop competition (Bleasdale 1960).

yield losses. These components are experimentally determined by measuring crop yield loss as a function of successive times of weed removal or weed emergence, respectively (Figure 14.2). Period thresholds can be used to predict when, rather than if, weeds must be controlled to prevent yield losses. Timely cultural weed control should aim at minimizing weed interference in crops at the critical period of competition in order to reduce yield losses. Figure 14.3 illustrates the negative effect of delayed weeding on crop yield and also the effect when weeding is timely.

2. Crop type and varieties: Crops differ in their competitive ability; barley is more tolerant of interference than wheat, and wheat is more tolerant than oats. Fast-canopy-forming and tall crops with extensive leaf area suffer less from weed competition.


4. Weed species: Tall morning glory (Ipomoea purpurea) is more competitive in cotton than sicklepod (Cassia obtusifolia) at similar weed densities. In general, annual broad-leaved weeds are more competitive than annual grass weeds at the same populations.

5. Soil type: The competitive effect of weeds varies depending on soil characteristics and fertility. At high levels of fertility, little appreciable
difference in crop yield occurs between weedy and weed-free crops. However, at low fertility levels, weedy crops yield less than weed-free crops.

6. Soil moisture: Comparative increases in yields of weedy and weed-free crops on moisture-deficient soils differ with crop and weed species. Minimal competition between soybean and *Setaria* spp. occurred when soil water content was either adequate or limiting during the entire season (Radosevich and Holt 1984).

7. Weed physiology: The C₄ photosynthetic mechanism might have adaptive value in weeds colonizing croplands where temperatures and light intensities are high. At midday when light intensity and temperature reach peak values, C₄ weeds fix carbon dioxide at much higher rates than crops
Critical period

Period 1  Period 2  Period 3

Weed biomass density

(Crop growth stage when weed competition causes maximum yield reduction.)

Critical period

Period 1  Period 2  Period 3

Weed biomass density

Cultural weeding

FIGURE 14.3 Untimely and timely cultural weeding with weed biomass removed after and before the critical period of weed-crop competition.
such as soybean and cotton. Weeds that have the C₄ mechanism include some grasses, *Amaranthus* spp. and *Setaria* species.

Recent evidence suggests that the presence of weeds in crop fields cannot automatically be judged damaging. Weed density/crop yield relationships are sigmoidal rather than linear. At low density, weeds do not usually affect yields, and under some circumstances, certain weeds even stimulate crop growth.

For example, in the rainfed areas of the Indian arid zone, weeds such as *Arnebia hispidissima*, *Borreria articulata*, and *Celosia argentea* increased growth and yield of bajra (*Pennisetum taphoideum*) but not of til (*Sesamum indicum*). The presence of *Indigofera cordiflora* was beneficial to both crops. Similarly, in northwest India, increases in the density of the leguminous weed *Triponello polycersta* resulted in increased dry weight of wheat, and only at very high densities of *T. polycersta* (about 3,200 plants per square meter) did wheat yield decline. This positive interaction seemed to be mediated by better nitrogen nutrition of wheat due to nodular bacteria present in the roots of *Triponella* (Kapoor and Ramakrishnan 1975).

Studies of this nature suggest that before stressing the importance of weed control, it should be made clear whether or not a particular "weed" is harmful to a specific crop in a given area.

The degree of competition between crops and weeds can be affected by manipulating several factors. The distance between crop rows, seeding rates, specific spatial and temporal crop arrangements, or various combinations of practices may influence the crop/weed balance (Buchanan 1977):

1. Spatial arrangement of plants: Narrower crop rows result in earlier sharing of the area between rows, thereby suppressing weed growth.
2. Crop seeding rate: In annual cereal crops, a high seeding rate may control weeds.
3. Date of planting: When crop germination coincides with emergence of the first flush of weeds, intense weed/crop interference results. One alternative is to delay planting so that yellow nutsedge can be cultivated after the first major flush of growth to reduce carbohydrates by 60 percent and subsequent vigor of the weed.
4. Crop sequence: Crop rotations may influence specific weed populations. In a literature survey of several studies, Liebman and Dyck (1993) found that crop rotation resulted in emerged weed densities in test crops that were lower in 21 cases, higher in one case, and equivalent in five cases in comparison to monoculture systems. In 12 cases where weed seed density was reported, seed density in crop rotation was lower in nine cases and equivalent in three cases when compared to monocultures of the component crops. Table 14.1 summarizes several studies that reported on weed dynamics in comparable crop rotation and monoculture systems. The success of rotation systems for weed suppression appears to be based on the use of crop
TABLE 14.1  Weed control through crop rotation: comparison with monoculture (after Liebman and Dyck 1993).

<table>
<thead>
<tr>
<th>Crop Rotation</th>
<th>Test Crop</th>
<th>Emerged Weed Density in Rotation</th>
<th>Test Crop Yield in Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. wheat/sugar beet</td>
<td>wheat</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>2. potato/potato/pea/sugar beet/sugar beet/wheat</td>
<td>wheat</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>3. wheat/red clover/potato/sugar beet/field bean</td>
<td>wheat</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>4. alfalfa (5 yr)/potato/sugar beet/pea/sugar beet/wheat</td>
<td>wheat</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>5. potato/oats/maize/field bean</td>
<td>oats</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>6. alfalfa (3 yr)/oats/sugar beet/sugar beet/oats</td>
<td>oats</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>7. fallow/winter rye/potato/oats + clover/clover/flax</td>
<td>winter rye</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>potato</td>
<td>equal</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>oats</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>clover</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>flax</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td>8. summer fallow/wheat</td>
<td>wheat</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>9. summer fallow/wheat</td>
<td>wheat</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>10. maize/maize/soybean</td>
<td>maize</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>11. maize/soybean/wheat</td>
<td>soybean</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>12. maize/peanut/cotton/soybean</td>
<td>maize</td>
<td>lower</td>
<td>equal</td>
</tr>
<tr>
<td></td>
<td>peanut</td>
<td>equal</td>
<td>equal</td>
</tr>
<tr>
<td></td>
<td>cotton</td>
<td>equal</td>
<td>equal</td>
</tr>
<tr>
<td></td>
<td>soybean</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>13. sugar beet/field bean/spring barley/winter rye/winter rape/winter wheat</td>
<td>sugar beet</td>
<td>higher</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>field bean</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>spring barley</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>winter rye</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>winter rape</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td>winter wheat</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td>14. winter wheat/maize</td>
<td>maize</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td>15. maize/winter wheat/maize</td>
<td>maize</td>
<td>lower</td>
<td>not available</td>
</tr>
<tr>
<td>16. winter wheat/maize/maize</td>
<td>maize</td>
<td>equal</td>
<td>not available</td>
</tr>
<tr>
<td>17. winter wheat/winter wheat/maize</td>
<td>maize</td>
<td>lower</td>
<td>not available</td>
</tr>
</tbody>
</table>
sequences that create varying patterns of resource competition, allelopathic interference, soil disturbance, and mechanical damage to provide an unstable and frequently inhospitable environment that prevents the proliferation of a particular weed species.

5. Crop mixtures: Intercropping can enhance a crop’s competitive abilities to suppress weeds. In a literature survey, Liebman and Dyck (1993) found that in intercropping systems where a main crop was intersown with a "smother" crop series, weed biomass in the intercrop was lower in 47 cases and higher in four cases than in the main crop grown alone; a variable response was observed in three cases. When intercrops were composed of two or more main crops, weed biomass in the intercrop was lower than in all of the component sole crops in 12 cases, intermediate between component sole crops in 10 cases, and higher than all sole crops in two cases. Intercrops demonstrate weed control advantages over sole crops in two ways. First, greater crop yield and less weed growth may be achieved if intercrops are more effective than sole crops in usurping resources from weeds or suppressing weed growth through allelopathy. Alternatively, intercrops may provide yield advantages without suppressing weed growth below levels observed in component sole crops if intercrops use resources that are not exploitable by weeds or convert resources to harvestable material more efficiently than sole crops. Weed suppressive intercropping systems include associations of maize-navy beans, sorghum-cowpea, barley-red clover, cassava-bean, pigeon pea-sorghum, cowpea, barley and red clover.

6. Cover crops: Certain fall-planted cover crops within orchards can greatly reduce weed populations and biomass in the next growing season. "Tecumseh" wheat desiccated in spring or fall can reduce weed weights 76 percent and 88 percent, respectively. In tropical plantation crops (coffee, cacao, coconut, and oil palm) the use of cover crops such as Centresoma pubescens, Peraria phaseoloides, P. javanica, and Calopogonium mucunoide is common for weed suppression (Akobundu 1987).

7. Mulching: Certain plant residues provide exceptional weed control. For example, sorghum and Sudan grass straw provided weed biomass reduction of 90 percent and 85 percent, repectively, whereas peat moss provided marginal reduction. Although the benefits of mulching are known by farmers, the logistics of procuring and transporting mulch limit its use in high cash-value crops. An alternative approach is to grow the mulch in situ, such as growing a legume (i.e., Mucuna prurien). Mucuna is established from seed and covers the ground within 10–12 weeks and dies off at the end of the rains leaving a thick mulch which provides ground cover for conservative tillage during the next cropping event. Fast-growing tree legumes such as Leucaena leucocephala grown in alley cropping are periodically pruned providing much biomass used as a mulch for weed control and to add organic matter to the soil (Akobundu 1987).
Allelopathy

Competition cannot always explain suppression of plant growth in agro-ecosystems. At times biochemical interactions (allelopathy) occur among plants. Allelopathy is any direct or indirect harmful effect by one plant on another through the production of chemical compounds released into the environment. Contrary to competition, allelopathy occurs by the addition of a toxic factor to the environment. Allelopathy is postulated as an important mechanism by which weeds affect crop growth, and vice versa (Altieri and Doll 1978, Putnam and Duke 1978, Gliessman 1982a). Evidence strongly suggests that certain cultivars of crops such as rye, barley, wheat, tobacco, and oats release toxic substances into the environment either through root exudation or from decaying plant material. Both allelopathy of the growing crop and of its residue might be utilized to reduce weed stands by suppressing germination and emergence of weeds and also by impacting weed growth. Residue of a certain rye line exhibited potential to reduce weeds in a no-till vegetable production system. Up to 95% control of weed biomass was obtained with the rye planted in the fall, killed in the spring, and vegetables planted in the residue (Aldrich 1984).

Wild types of existing crops may have possessed high allelopathic potential and this characteristic may have declined or disappeared as they were crossed and selected for other characteristics. Some accessions of Avena sp. have been shown to exhibit allelopathic influences on wild mustard (Brassica kaber). Similarly, cucumber accessions demonstrated allelopathic potential against Brassica kaber and a grass, Panicum miliaceum, under controlled environmental conditions. Under certain field conditions selected cucumbers inhibited the growth of prosomillet, barnyard grass, and redroot pigweed. Further bioassay tests were conducted to confirm that the inhibition was due to a toxin produced by certain cucumbers.

Little effort has been devoted to developing crops with allelopathic potential by crossing current crop varieties with wild types. The allelopathic influence is often observed to be strongest when plants approach maturity, suggesting it could be put to best use with incipient weed problems, well after the crop has become established. Such a phenomenon would certainly be of value in influencing late-season weed control.

Allelopathy may become a viable means of weed control provided that these traits occur in wild types of cultivated species and they can be transferred to desirable cultivars. Achieving weed control by this means is inexpensive, non-polluting, and requires no labels or application paraphernalia. Several alternatives exist to exploit allelopathy in agriculture:
• Synthesize these products or their analogues for use as herbicides by isolating and identifying the toxic natural products.
• Incorporate the toxic mechanism into cultivars through genetic manipulation.
• Use allelopathic cover crops, mulches, and residues.
• Manipulate weed seed behavior by using plant compounds to enhance early germination of weed seeds.

Studies comparing competitive and allelopathic components of interference between crops and weeds will establish the tolerance levels of the different weed species for each crop type.

When a crop and its accompanying weed species are considered as integral parts of the same agroecosystem, as can be observed in agroecosystems where non-crop plants are classified and managed, it becomes increasingly important to understand the complexities of the relationships between the component plant parts and the environment. Studies of the mechanisms of biotic interference between the crop and non-crop components, especially through allelopathic interactions, will become more important as the economic and ecological limitations on modern weed control practices become more restrictive. Allelopathy offers a potential alternative (Gliessman 1982a).

Weed Management

With changes in the relative frequencies of aggressive weed species associated with changing cropping sequences, cultivation regimes, and herbicide applications, it is becoming increasingly obvious that more than one management procedure is needed to deal with the dominant weed complexes. Consequently, weed scientists have started to develop an integrated approach to weed problems, aimed at maintaining the growth of weeds at ecologically, agronomically and economically acceptable levels. The approach is based on an understanding of the cultural, biological, and abiotic factors causing seasonal changes in weed populations.

The central objective of weed management is to manipulate the crop/weed relationship so that growth of the crop is favored over that of the weed. Efforts have been directed at preventing weed reproduction, interrupting the recycling of weed propagules, preventing introduction of new weeds, minimizing conditions that provide niches for weed invasion, and overcoming adaptations that enable weeds to persist in disturbed habitats. The main approaches emphasized include: (a) reduction of the propagules produced, (b) reduction of weed emergence, and (c) minimization of weed competition and interference. Cropping practices (choice of crop, rotation, crop spacing, seeding rate), tillage practices (tillage depth, minimum tillage,
crop residue management), and herbicide practices are commonly used to achieve these objectives. Figures 14.4a and 14.4b provide a suggestion for reducing numbers of propagules in the seed bank, for preventing weed emergence with crops, and for reducing crop-weed competition within the context of a total management program.

Any weed management program is only part of a total crop production system, so any combination of environmental manipulation, crop competition, or improved cultural management techniques aimed at reducing weed levels must be compatible with other farm management schemes. In this regard, interactions between weed and pest management programs are particularly important. The farmer's soil fertility scheme is also important, as it can affect crop/weed interactions in unique ways.

Ecologists have stressed the importance of determining site-specific crop/weed relationships in terms of resource limitation, germination, and growth rates. It is also important to identify the environmental interaction

![Diagram](image_url)

**CONTROL PRACTICES**
- Release biotic agents to inhibit seed production.
- Release biotic agents to maintain perennials at subeconomic threshold levels.
- Apply herbicides to prevent seed production, viability, and dormancy.
- Apply herbicides to hasten germination.
- Manipulate soil microorganisms to strip weed seeds of their protection from decay.

**TILLAGE PRACTICES**
- Leave weed seeds on the soil surface for overwintering.
- Bring perennating parts to the soil surface for overwintering.
- Shallow-till periodically.

**CROPPING PRACTICES**
- Shade weeds during flowering with cultivars selected for shading characteristics, planting patterns to provide an early canopy, and/or cover crops that fill gaps between harvested crops.
- Use crop cultivars allelopathic toward reproduction of weeds.
- Time nitrogen fertilizing to encourage vegetative growth of perennial weeds.

**FIGURE 14.4a Summary of conceptual approaches for reducing numbers of propagules in the weed seed bank.**

FEWER PROPAGULES IN SOIL

WEEDS

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CONTROL PRACTICES
Apply preplant-incorporated or preemergence herbicides.
Concentrate residues of allelopathic plants in the zone of weed seed germination.
Before planting:
Break seed or perennating part dormancy, then destroy emerged plants. Leach out germination inhibitors then destroy emerged plants.

CROPPING PRACTICES
Switch to crops planted either early or later than the flush of weed emergence.
Use cultivars allelopathic toward germinating/emerging weeds.

TILLAGE PRACTICES
Deeply bury (plow) seeds.
Delay final tillage until flush of germination has occurred.
Fragment perennating parts with tillage, then deep plow.
Deeply bury (plow) perennating parts.

FIGURE 14.4b Summary of conceptual approaches for preventing weed emergence with crops.

of weeds and the response of weeds to agroecosystem management to predict weed abundance and/or population shifts. Evidence suggests that in some circumstances manipulating one or two factors (cultivar composition, crop density, row spacing, planting date, water management, rate of applied nitrogen, tillage, crop mixture) can favorably shift the crop/weed balance. In its simplest form, weed management consists of exploiting the understanding of these relationships (Altieri and Liebman 1988).

Perhaps too much emphasis has been given to weed research and the manipulation of crop genotypes so that the competitive relationships between crops and weeds shift in favor of the crop. Ghersa and Roush (1993) argue that pursuing strategies to reduce yield losses by improving the capability of a crop to compete against weeds is less profitable than pursuing strategies that seek to manage dispersal and distribution of weed propagules. For this reason, they believe that better understanding of the ways that weed propagules disperse may lead to more permanent solutions for weed problems.
Once the principles governing relationships of germination, growth, and competition have been determined, management can be suggested to affect the weed community of several agroecosystems. For example, if the competitive ability of a key weed species is based on early germination, the best choice may be to plant and cultivate early. If rapid growth and canopy development are the most important strategies, times of control, weed density thresholds, and fast-growing temporal and spatial crop combinations should be considered. Other relevant ecological principles on which non-chemical weed control practices can be based are shown in Table 14.2.

Perhaps the major contributions that agroecologists can make to weed management are:

1. To determine the ecological factors governing weed abundance
2. To discern the conditions and times under which weeds would be most vulnerable to management tactics

<table>
<thead>
<tr>
<th>Ecological Principle</th>
<th>Weed Control Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce inputs to and increase outputs from soil seed bank</td>
<td>Prevention</td>
</tr>
<tr>
<td></td>
<td>Soil solarization</td>
</tr>
<tr>
<td></td>
<td>Weed control before seed set</td>
</tr>
<tr>
<td>Allow crop earlier space (resource) capture</td>
<td>Early cultivation</td>
</tr>
<tr>
<td></td>
<td>Using crop transplants</td>
</tr>
<tr>
<td></td>
<td>Choice of planting date</td>
</tr>
<tr>
<td>Reduce weed growth and thus space capture</td>
<td>Cultivation</td>
</tr>
<tr>
<td></td>
<td>Mowing</td>
</tr>
<tr>
<td></td>
<td>Mulching</td>
</tr>
<tr>
<td>Maximize crop growth and adaptability</td>
<td>Choice of crop variety</td>
</tr>
<tr>
<td></td>
<td>Early planting</td>
</tr>
<tr>
<td>Minimize intraspecific competition of crop, maximize crop space capture</td>
<td>Choice of seeding rate</td>
</tr>
<tr>
<td></td>
<td>Choice of row spacing</td>
</tr>
<tr>
<td>Maximize competitive effects of crop on weed</td>
<td>Planting smoother or cover crops</td>
</tr>
<tr>
<td>Modify environment to render weeds less well-adapted</td>
<td>Rotation of crops</td>
</tr>
<tr>
<td></td>
<td>Rotation of control methods</td>
</tr>
<tr>
<td>Maximize efficiency of resource utilization by crops</td>
<td>Intercropping</td>
</tr>
</tbody>
</table>
3. To provide information for accurate prediction of the responses of weeds to various control practices and cropping patterns
4. To elucidate the functional linkages between weeds, crops, and other species

Such studies can greatly contribute to an understanding of the temporal and spatial dynamics of weed communities in agricultural ecosystems (Radosevich and Holt 1984).

Realistically, however, it may not be possible to know everything about a weed species in order to develop an effective weed management strategy. Achievement of practical weed suppression in an agroecosystem may require knowledge of only a few biological features and key functional relationships of the weed in question. This in turn may imply changes in only a few key agricultural management decisions. The issue then is to identify and apply key ecological processes and factors that govern weed dynamics and interaction in agroecosystems. The following steps can lead to a better understanding of key interactions and susceptible weed life cycle stages for better management of specific crop/weed assemblages in local agroecosystems (Altieri and Liebman 1988):

1. Monitor both seed and vegetative plant populations, as joint consideration of active and passive parts of weed populations is the only effective way to understand life histories of weed species.
2. Identify weed species that are causing problems, as there are no clear competitive hierarchies of crops and weeds. Determine when, and at what densities, does a particular weed species or weed complex affect the yield of a specific crop, and how long this effect lasts. Such studies will determine the degree of weed control needed and the type of control.
3. Study the farmers' existing methods of weed control and their attitudes toward weeds.
4. Assess the most significant weed species or weed complexes and clarify their interaction with insects, pathogens, and other agroecosystem biotic and abiotic components.
5. Predict weed populations, based on information of past cropping shifts over time as management, crop sequences, and other factors change.
6. Decide whether to apply a control measure, based on seed populations in the soil and thresholds previously established, which consider economic as well as social factors and history of the field. Assess ecological factors of the population.
7. Choose technology compatible with total systems (i.e., insect management programs, fertilization, etc.), because weed management strategies are likely to interact with other pest control programs in most situations.
8. Recommended weed management programs must take into account the farmers' needs and resource base. If a certain weed control technology is only accessible to a specific group of farmers in a region, it can affect farmers'
economic differentiation in unequal ways. On the other hand, if farmers resist a technology, this may have an ecological basis.

9. Integrate weed protection measures with other crop management practices and wait awhile before deciding on the need for further protection after a certain period.

10. Evaluate the long-term environmental, social, and economic impact of the proposed weed management system.

The Ecological Role of Weeds

The environmental simplification that characterizes modern agricultural systems has accelerated plant succession patterns in agriculture, creating specialized habitats that favor the selection of competitive and opportunistic weeds. Although weeds interfere with agricultural production, they are important biological components of agroecosystems and may be considered useful (Sagar 1974).

In many areas of Mexico, for example, local farmers do not completely clear all weeds from their cropping systems. This "relaxed" weeding is usually seen by agriculturalists as the consequence of a lack of labor and low return for the extra work. However, a closer look reveals that certain weeds are managed and even encouraged if they serve a useful purpose. In the lowland tropics of Tabasco, Mexico, there is a unique classification of non-crop plants according to use potential on one hand and effects on soil and crops on the other. Under this system, farmers recognized 21 plants in their cornfields classified as mal monte (bad weeds) and 20 as buen monte (good weeds). The good weeds serve as food, medicines, ceremonial materials, teas, and soil improvers (Chacon and Gliessman 1982).

Similarly, the Tarahumara Indians in the Mexican Sierra depend on edible weed seedlings (Amaranthus, Chenopodium, Brassica) from April through July, a critical period before maize, bean, cucurbits, and chiles mature in August through October. Weeds also serve as alternative food supplies in seasons when the maize crops are destroyed by frequent hailstorms. In a sense, the Tarahumara practice a double crop system of maize and weeds that allows for two harvests; one of weed seedlings or quelites early in the growing season, and another in the harvested maize late in the growing season (Bye 1981).

Weeds interact ecologically with all the other subsystems of an agroecosystem and are valuable in erosion control, conservation of soil moisture, buildup of organic matter and nitrogen in the soil and preservation of beneficial insects and wildlife (Gliessman et al. 1981). It is also a poorly recognized benefit that the soil cover provided by weeds can aid substantially in controlling erosion. One study conducted in Malawi cornfields showed that weedy ground cover reduced soil erosion losses from 12.1 tons
298 per hectare on weeded plots to 4.5 tons per hectare on unweeded plots. An annual saving of approximately eight tons per hectare of soil should be a potentially great enough benefit to offset long-term yield reductions (Weil 1982).

A number of weeds within or around traditional cropping systems in developing countries are wild relatives of crop plants. The ecological amplitudes of wild relatives may exceed those of the crops derived from or otherwise related to them, a feature exploited by plant breeders to enhance the resistance or adaptive range of crops. In these settings, land races and wild and weedy relatives have coexisted and coevolved over a long period of time with each other and with human cultures. Cycles of natural hybridization and introgression have often occurred between crops and wild relatives, increasing the variability and genetic diversity available to farmers. Through the practice of nonclean cultivation, farmers have inadvertently increased the gene flow between crops and their relatives. For example, in Mexico farmers allow teosinte to remain within or near cornfields, so that some natural crosses occur when the wind pollinates corn. Although crosses such as these are not immediately evident, the maize-teosinte seeds produce hybrid plants the following year when the new maize crop is planted from last year's seeds (Altieri and Liebman 1988).

Such hybrids and their descendants are phenotypically distinct and fertile, and thus capable of passing on their genetic traits. In this way, weeds remain important genetic resources that must be preserved, for their genes are valuable in improving the performance of our existing crops, especially in marginal areas.

Perhaps the ecological role of weeds can be best visualized by analyzing the possible consequences of a complete eradication of the weed flora from agroecosystems. Some of these include (Tripathi 1977):

- Replacement of herbicide-susceptible weed species by more resistant ones
- Decrease in total production per unit area, because of the removal of plant biomass
- Drastic reduction in genetic resources, since weeds contribute substantially to the existing gene pool
- Crop plants falling victim to insects or pathogens that have so far preferred weeds
- Reduction in the abundance of certain beneficial insects and wildlife that use weeds as alternative sources of food, shelter, and breeding sites
- Increase of erosion problems after crop harvest
- Loss of nutrients otherwise mined and stored by weeds

An objective analysis of the problems mentioned above should set the stage for an emphasis on weed management rather than weed control. The
ecological basis of this change in emphasis has been elaborated by Bantilan et al. 1974, Buchanan and Frans 1979, Harper 1977, Sagar 1974, Tripathi 1977, and others. This re-examination of the role of weeds as ecological components can, in fact, lead to the development of guidelines for total agroecosystem management.

Weeds as Sources of Insect Pests in Agroecosystems

Weeds have traditionally been considered unwanted plants that reduce yields by competing with crops or by harboring insect pests and plant diseases. Between 1934 and 1963 there were 442 references relating to weeds as reservoirs of pests; 100 such references concern cereals (van Emden 1965). The Ohio Agricultural Research and Development Center published a series of publications concerning weeds as reservoirs for organisms affecting crops. More than 70 families of arthropods affecting crops were reported as primarily weed-associated (Bendixen and Horn 1981). More detailed examples of the role of weeds in the epidemiology of insect pests and plant diseases can be found in Thresh (1981).

Weedy plants near crop fields can provide the requisites for pest outbreaks. The presence of *Urtica dioica* in the host layer of non-crop habitats surrounding carrot fields was the most important factor determining high levels of carrot fly larval damage to adjacent carrots. Adult leafhoppers invade peach orchards from edge vegetation and subsequently colonize trees whose ground cover is composed of preferred wild hosts. Plantains (*Plantago* spp.) provide alternative food for the rosy apple aphid *Dysaphis plantaginea*, an important pest of apple in England. The rosy apple aphid spends most of the summer on plantain, returning to apple in late summer. The dock sawfly *Ametrastegia glabrata* normally feeds on docks (*Rumex* spp.) and knotgrass (*Polygonum* spp.), and the larvae of the last generation can move on to adjacent apple trees and bore into fruits or shoot tips (Altieri and Letourneau 1982, Altieri 1993).

The Role of Weeds in the Ecology of Natural Enemies

Certain weeds are important components of agroecosystems that can positively affect the biology and dynamics of beneficial insects. Weeds serve as alternative sources of prey/hosts, pollen, or nectar, and provide microhabitats that are not available in weed-free monocultures (van Emden 1965). The beneficial entomofauna associated with many weed species has been surveyed (Altieri and Whitcomb 1979).

In the last 20 years, research has shown that outbreaks of certain types of crop pests are more likely to occur in weed-free fields than in weed-diversified crop systems (Altieri et al. 1977). High density crop fields with
a dense weed cover usually have more predaceous arthropods than do weed-free fields. Ground beetles (Carabidae), syrphids (Syrphidae) and lady beetles (Coccinellidae) are abundant in weed-diversified systems. Relevant examples of cropping systems in which the presence of specific weeds has enhanced the biological control of particular pests are given in Table 14.3.

Spectacular parasitism increase has been observed in annual crops and orchards with rich undergrowths of wild flowers. In apple, parasitism of tent caterpillar eggs and larvae and codling moth larvae was 18 times greater in those orchards with floral undergrowths than in orchards with sparse floral undergrowth. Soviet researchers at the Tashkent Laboratory found that lack of adult food supply was the reason for the inability of *Aphytis proclia* to control its host, the San Jose scale (*Quadraspidiotus perniciosus*). The effectiveness of the parasitoid improved as a result of planting a *Phacelia* sp. cover crop in the orchards. Three successive plantings of *Phacelia* increased scale parasitization from 5% in clean cultivated orchards to 75% where these nectar producing plants were grown. These Russian researchers also noted that *Apanteles glomeratus*, a parasite of two cabbageworm species (*Pieris* spp.) on crucifer crops, obtained nectar from wild mustard flowers. The parasites lived longer and laid more eggs when these weeds were present. When quick-flowering mustards were actually planted in the fields with cole crops, parasitization of the host increased from 10% to 60% (Altieri 1993b).

Some entomophagous insects are attracted to particular weeds, even in the absence of host or prey, by chemicals released by the herbivore's host plant or other associated plants (Altieri et al. 1981). For example, the parasitic fly *Eucelatoria* sp. prefers okra to cotton, and the wasp *Peristenus pseudopallipes*, which attacks the tarnished plant bug, prefers *Erigeron* to other weed species (Monteith 1960, Nettles 1979).

Of significant practical interest are the findings of Altieri et al. (1981), which showed that parasitization rates of *Heliothis zea* eggs by *Trichogramma* sp. were greater when the eggs were placed on soybeans next to corn and the weeds *Desmodium* sp., *Cassia* sp., and *Croton* sp. than on soybeans grown alone. Although the same number of eggs were placed on soybean and on the associated plants, few of the eggs placed on the weeds were parasitized, suggesting that these plants were not actively searched by *Trichogramma* sp. but nevertheless enhanced the efficiency of parasitization on the associated soybean plants. It is possible that they emitted volatiles with kairomonal action. Further tests showed that application of water extracts of some of these associated plants (especially *Amaranthus* sp.) to soybean and other crops enhanced parasitization of *H. zea* eggs by *Trichogramma* spp. wasps. The authors stated that a stronger attraction and retention of wasps in the extract treated plots may be responsible for the higher parasitization levels. The possibility that vegetationally complex plots are more chemically diverse
TABLE 14.3 Selected examples of cropping systems in which the presence of weeds enhanced the biological control of specific crop pests (based on Altieri and Letourneau 1982 and Andow 1991).

<table>
<thead>
<tr>
<th>Cropping systems</th>
<th>Weed species</th>
<th>Pest(s) regulated</th>
<th>Factor(s) involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>Natural blooming weed complex</td>
<td>Alfalfa caterpillar (Colias eurytheme)</td>
<td>Increased activity of the parasitic wasp (Apanteles medicaginis).</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Grass weeds</td>
<td>Empoasca fabae</td>
<td>?</td>
</tr>
<tr>
<td>Apple</td>
<td>Phacelia sp. and Eryngium sp.</td>
<td>San Jose scale (Quadraspisditus perniciosus) and aphids.</td>
<td>Increased activity and abundance of parasitic wasps (Aphelinis mali and Aphytis proclia).</td>
</tr>
<tr>
<td>Apple</td>
<td>Natural weed complex</td>
<td>Tent caterpillar (Malacosoma americanum) and codling moth (Carpocapsa pomonella)</td>
<td>Increased activity and abundance of parasitic wasps.</td>
</tr>
<tr>
<td>Beans</td>
<td>Goosegrass (Eleusine indica) and red sprangletop (Leptochloa filiformis)</td>
<td>Leaffoppers (Empoasca kraemeri)</td>
<td>Chemical repellency or masking.</td>
</tr>
<tr>
<td>Broccoli</td>
<td>Wild mustard</td>
<td>Phyllotreta cruciferae</td>
<td>Trap cropping.</td>
</tr>
<tr>
<td>Brussels sprouts</td>
<td>Sperpula arvensis</td>
<td>Delia brassicae</td>
<td>?</td>
</tr>
<tr>
<td>Brussels sprouts</td>
<td>Spergula arvensis</td>
<td>Mamestra brassicae (Brevisystis sp., Brevisystis brassicae)</td>
<td>Increase of predators and interference with colonization.</td>
</tr>
<tr>
<td>Cabbage</td>
<td>Crataegus sp.</td>
<td>Diamondback moth (Plutella maculipennis)</td>
<td>Provision of alternate hosts for parasitic wasps (Herogones sp.).</td>
</tr>
<tr>
<td>Citrus</td>
<td>Natural weed complex</td>
<td>Mites Eotetranychus sp., Panonychus citri, Metaeteiranychus citri</td>
<td>?</td>
</tr>
<tr>
<td>Citrus</td>
<td>Natural weed complex</td>
<td>Diaspidid scales</td>
<td>?</td>
</tr>
<tr>
<td>Coffee</td>
<td>Natural weed complex</td>
<td>Pentatomid Antestiopus intricata</td>
<td>?</td>
</tr>
<tr>
<td>Collards</td>
<td>Ragweed (Ambrosia artemisifolia)</td>
<td>Flea beetle (Phyllostreta cruciferae)</td>
<td>Chemical repellency or masking.</td>
</tr>
</tbody>
</table>
### TABLE 14.3 continued

<table>
<thead>
<tr>
<th>Cropping systems</th>
<th>Weed species</th>
<th>Pest(s) regulated</th>
<th>Factor(s) involved</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Collards</strong></td>
<td><em>Amaranthus retroflexus,</em> <em>Chenopodium album,</em> <em>Xanthium strumarium</em></td>
<td>Green peach aphid (<em>Myzus persicae</em>)</td>
<td>Increased abundance of aphid predators (<em>Chrysopa carnea,</em> <em>Coccinellidae,</em> <em>Syrphidae</em>).</td>
</tr>
<tr>
<td><strong>Corn</strong></td>
<td>Giant ragweed</td>
<td>European corn aphid (<em>Ostrinia nubilalis</em>)</td>
<td>Provision of alternate hosts for the tachinid parasite <em>Lydella grisesens.</em></td>
</tr>
<tr>
<td><strong>Corn</strong></td>
<td>Natural weed</td>
<td><em>Heliothis</em> sea, <em>Spodoptera frugiperda</em></td>
<td>Enhancement of predators.</td>
</tr>
<tr>
<td><strong>Corn</strong></td>
<td>Setaria viridis and <em>S. faberi</em></td>
<td><em>Diabrotica virgifera</em> and <em>D. barberi</em></td>
<td>?</td>
</tr>
<tr>
<td><strong>Cotton</strong></td>
<td>Ragweed</td>
<td>Boll weevil (<em>Anthonomus grandis</em>)</td>
<td>Provision of alternate hosts for parasite <em>Eurytoma tylodermalis.</em></td>
</tr>
<tr>
<td><strong>Cotton</strong></td>
<td>Ragweed and <em>Rumex crispus,</em> <em>Cassia adenacea</em></td>
<td><em>Heliothis</em> spp.</td>
<td>Increased populations</td>
</tr>
<tr>
<td><strong>Cotton</strong></td>
<td><em>Salvia coccinea,</em> <em>Lygus sp.</em></td>
<td></td>
<td>?</td>
</tr>
<tr>
<td><strong>Cruciferae crops</strong></td>
<td>Quick-flowering mustards</td>
<td>Cabbage worms (<em>Pieris</em> spp.)</td>
<td>Increased activity of parasitic wasps (<em>Apanteles glomeratus</em>)</td>
</tr>
<tr>
<td><strong>Mung</strong></td>
<td>Natural weed complex</td>
<td>Beanfly (<em>Ophlomyia phaseoli</em>)</td>
<td>Alteration of colonization beans background.</td>
</tr>
<tr>
<td><strong>Oil palm</strong></td>
<td><em>Pueraria</em> sp., <em>Flemingia</em> sp., <em>ferns,</em> <em>grasses,</em> and <em>creepers</em></td>
<td><em>Scarab</em> beetles (<em>Xyloryctes</em> sp. and <em>Chalcosoma atlas</em>)</td>
<td>?</td>
</tr>
<tr>
<td><strong>Peach</strong></td>
<td>Ragweed</td>
<td>Oriental fruit moth</td>
<td>Provision of alternate hosts for the parasite <em>Macrocentrus ancyloverus.</em></td>
</tr>
<tr>
<td><strong>Peach</strong></td>
<td>Rosaceous weeds and <em>Dactylis glomerata</em></td>
<td>Leafhoppers (<em>Paraphlepsius</em> sp. and <em>Scaphytoptus</em> sp.)</td>
<td>?</td>
</tr>
<tr>
<td><strong>Sorghum</strong></td>
<td><em>Helianthus</em> spp.</td>
<td><em>Schizophas graminum</em></td>
<td>Enhancement of <em>Aphelinus</em> spp. parasitoids.</td>
</tr>
<tr>
<td><strong>Soybean</strong></td>
<td>Broadleaf weeds grasses</td>
<td><em>Epilachira varivestis</em></td>
<td>Enhancement of predators.</td>
</tr>
<tr>
<td><strong>Soybean</strong></td>
<td><em>Cassia obtusifolia</em></td>
<td><em>Nezara viridula,</em> <em>Anticarsia gemmatalis</em></td>
<td>Increased abundance of predators.</td>
</tr>
<tr>
<td><strong>Soybean</strong></td>
<td><em>Crotonaria</em> sp.</td>
<td><em>Nezara viridula</em></td>
<td>Enhancement of tachinid <em>Trichopoda</em> sp.</td>
</tr>
<tr>
<td><strong>Sugar-</strong></td>
<td><em>Euphorbia</em> ssp. weeds</td>
<td>Sugarcane weevil (<em>Rhuddosielus obscurus</em>)</td>
<td>Provision of nectar and pollen cane for the parasite <em>Lixophaga sphenophori.</em></td>
</tr>
<tr>
<td><strong>Sugar-</strong></td>
<td>Grassy weeds</td>
<td>Aphid <em>Rhopalsiphum maidis</em></td>
<td>Destruction of alternate cane host plants.</td>
</tr>
<tr>
<td>Cropping systems</td>
<td>Weed species</td>
<td>Pest(s) regulated</td>
<td>Factor(s) involved</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------------------------</td>
<td>-------------------------------------</td>
<td>--------------------------------------------------------</td>
</tr>
<tr>
<td>Sugar-cane</td>
<td><strong>Borreria verticillata</strong> and <strong>Hyptis atrorubens</strong></td>
<td>Cricket (<strong>Scapteriscus vicinus</strong>)</td>
<td>Provision of nectar for the parasite <strong>Larra americana</strong>.</td>
</tr>
<tr>
<td>Sweet potatoes</td>
<td><strong>Morning glory</strong> (<strong>Ipomoea sp.</strong>))</td>
<td><strong>Argus tortoise</strong> (<strong>Chelymorpha cassidea</strong>)</td>
<td>Provision of alternate hosts for parasite <strong>Emersonella sp.</strong></td>
</tr>
<tr>
<td>Vegetable crops</td>
<td><strong>Wild carrot</strong> (<strong>Daucus carota</strong>)</td>
<td><strong>Japanese beetle</strong> (<strong>Popillia japonica</strong>)</td>
<td>Increased activity of the parasitic wasp <strong>Tiphia popilliavera</strong>.</td>
</tr>
<tr>
<td>Vineyards</td>
<td><strong>Wild blackberry</strong> (<strong>Rubus sp.</strong>)</td>
<td><strong>Grape leafhopper</strong> (<strong>Erythroneura eleganella</strong>)</td>
<td>Increase of alternate hosts for the parasitic wasp <strong>Anagrus epos</strong>.</td>
</tr>
<tr>
<td>Vineyards</td>
<td><strong>Johnson grass</strong> (<strong>Sorghum halepense</strong>)</td>
<td><strong>Pacific mite</strong> (<strong>Eotetranychus willaimetii</strong>)</td>
<td>Buildup of predaceous mites <strong>(Metaseiulus occidentalis)</strong>.</td>
</tr>
</tbody>
</table>

than monocultures, and therefore more acceptable and attractive to parasitic wasps, opens new dimensions for biological control through weed management and behavior modification.

Work in Colombia provided experimental evidence of insect pest reduction in weed-diversified annual crops. Adult and nymph densities of *Empoasca kraemeri*, the main bean pest of the Latin American tropics, were reduced significantly as weed density increased in bean plots. Conversely, the chrysomelid *Diabrotica balteata* was more abundant in diversified bean habitats than in bean monocultures, although bean production was not affected because feeding on weeds diluted the injury to beans. In other experiments *E. kraemeri* populations were reduced significantly in weedy habitats, especially in bean plots with grass weeds (*Eleusine indica* and *Laeptochloa filiformis*). *D. balteata* densities fell by 14 percent in these systems. When grass-weed borders one meter wide surrounded bean mono-cultures, densities of adults and nymphs of *E. kraemeri* fell drastically. When bean plots were sprayed with a water homogenate of fresh grass-weed leaves, adult leafhoppers were repelled; continuous applications affected the reproduction of leafhoppers, as evinced by a reduction in the number of nymphs (Altieri et al. 1977).

Populations of insect pests and associated predaceous arthropods were sampled in simple and diversified maize habitats at two sites in north Florida during 1978 and 1979. Through various cultural manipulations, characteristic weed communities were established selectively in alternate rows with corn plots (Altieri and Letourneau 1982). Fall armyworm (*Spodoptera frugiperda*) incidence was consistently higher in weed-free habitats than in the corn containing natural weed complexes or selected weed associations. Corn earworm (*Heliothis zea*) damage was similar in all weed-free and weedy
treatments, suggesting that this insect is not affected greatly by weed diversity.

The distance between plots was reduced in one site. While predators moved freely between habitats, it was difficult to identify between-treatment differences in the composition of predator communities. In the other site, increased distances between plots minimized such migrations, resulting in greater population densities and diversity of common foliage insect predators in the weed-manipulated corn systems than in the weed-free plots. Trophic relationships in the weedy habitats were more complex than food webs in monocultures.

Weeds within a crop system can reduce pest incidence by enticing pest insects away from the crop. For example, flea beetles, *Phyllotreta cruciferae*, concentrate their feeding more on the intermingled *Brassica campestris* plants than on collards (Altieri and Gliessman 1983). The weed species had significantly higher concentrations of allylisothiocyanate (a powerful attractant of flea beetle adults) than collards, thus diverting the beetles from the crops. Similarly, in Tlaxcala, Mexico, the presence of flowering *Lupinus* spp. in tasseling cornfields often diverts the attack of the scarab beetle, *Macrodactylus* sp. from female corn flowers to lupine flowers (Trujillo-Arriaga and Altieri 1990).

In England, winter barley plots with grass weeds had less aphids and more than ten times the number of staphylinid beetles than plots without weeds (Burn 1987). Similarly, spring-planted alfalfa plots infested with weeds had a less diverse substrate predator complex but a greater foliage predator complex than did weed-free plots (Barney et al. 1984). The carabid *Harpalus pennsylvanicus* and foliage predators (i.e., *Orius insidiosus* and Nabidae) were more abundant in alfalfa fields where grass weeds were dominant.

Smith (1969) concluded that weeds within brussels sprouts enhanced natural enemy action against aphids by providing predator oviposition sites. This partly explained the lower aphid populations recorded in weedy plots. By selectively allowing a cover of *Spergula arvensis* within brussels sprouts plots, populations of *Mamestra brassicae*, *Evergestis forficalis*, cabbage root fly, and *Brevicoryne brassicae* were drastically reduced (Theunissen and den Ouden 1980).

**Weed Management to Regulate Insect Pests**

Based on the evidence discussed above, it seems that by encouraging the presence of specific weeds in crop fields, it is possible to improve the biological control of certain insect pests (Altieri and Whitcomb 1979). Naturally, careful manipulation strategies need to be defined in order to avoid weed competition with crops and interference with certain cultural
practices. In other words, economic thresholds of weed populations need to be defined, and factors affecting crop/weed balance within a crop system should be understood (Bantilan et al. 1974).

Weed management involves shifting the crop/weed balance so that crop yields are not economically reduced. This may be accomplished with herbicides, through selective cultural practices or by manipulating crops to favor crop cover rather than weeds. Suitable levels of weeds that support populations of beneficial insects can be attained within fields by designing competitive crop mixtures, allowing weed growth in alternate rows or in field margins only, use of cover crops, adoption of close row-spacings, providing weed-free periods (e.g., keeping crops free of weeds during the first third of their growth cycle from sprouting to harvest), mulching and cultivation regimes. In the state of Georgia, populations of the velvet bean caterpillar (Anticarsia gemmatalis) and of the southern green stink bug (Nezara viridula) were greater in weed-free soybeans than in either soybeans left weedy for two or four weeks after crop emergence, or for the whole season (Altieri et al. 1981).

Changes in the species composition of weed communities are also desirable to ensure the presence of plants that affect insect dynamics. Weedy species can be manipulated by several means (Altieri and Whitcomb 1979), such as changing levels of key chemical constituents in the soil, using herbicides that suppress certain weeds but encourage others, sowing desired weed seeds, and varying weed species composition by altering the date of plowing.
Plant Disease Ecology and Management

Plant pathologists recently have emphasized that disease epidemics are more frequent in crops than in natural vegetation. This observation has led to the view that disease epidemics are largely the result of human interference in "the balance of nature" (Thresh 1982). The conditions that enable a pathogen to increase to epidemic levels are particularly favored by the widespread culture of genetically and horticulturally homogeneous crops, a common trend in many modern crop systems (Zadoks and Schein 1979). Extensive plantings close to major foci are particularly vulnerable, and invasion of remote sites is facilitated by the presence of intervening areas of susceptible hosts.

Epidemiology and Disease Management

Stated briefly, conditions necessary for the wide-scale development of a damaging disease are (Berger 1977):

1. The virulent race of the pathogen (fungi, bacteria, or virus) must be present in low frequency in the host (crop).
2. The host (crop) that is susceptible to this race must be widely distributed in a region.
3. Environmental conditions must be favorable for development of the pathogen.

Together these factors form a disease triangle; their incidence and interaction result in plant disease. Indeed, disease will not build up unless there is an active pathogen, a suitable host, and suitable environmental conditions for infection, colonization, and reproduction of the pathogen. Environmental
factors conducive to disease include temperature, light, relative humidity, and so on, but also irrigation, which changes the crop microclimate and chemical fertilization (especially N) to promote luxuriant vegetative growth and increased succulence of host plants. Environmental factors also affect the competitive ability of the pathogen when in the soil (Manners 1993). Increasing knowledge of the host/pathogen/environment disease triangle has enabled pathologists to apply certain ecological principles to reduce losses from epidemic disease. Although crops differ greatly in the type, permanence, and stability of the habitat they provide for diseases, several features that can affect the spread of disease in agroecosystems can be recognized. (Table 15.1)

The intensification of agriculture includes several practices which favor plant disease:

1. Enlargement of fields
2. Aggregation of fields
3. Increase in the density of host crops
4. Decrease in diversity of the species and at the varietal level of host populations
5. Increase of monoculture and/or short rotational patterns
6. Use of fertilization, irrigation, and other crop environmental modifications

There is a direct relation between the intensity of cultivation and disease risk. Clearly, extensive and semi-intensive systems of cereals or potato in Asia, Argentina, or eastern Europe have lower disease risk than intensive systems of the United States or western Europe (Zadoks and Schein 1974).

The purpose of disease control is to prevent disease damage from exceeding that level where profit or required yield is significantly diminished. In general, three epidemiological strategies can be applied to minimize losses due to disease:

1. Eliminate or reduce the initial inoculum \(X_0\) or delay its appearance at the beginning of the season.
2. Slow or decrease the rate of diverse development \(r\) during the growing period.
3. Shorten the time of exposure of the crop to the pathogen by using short-season varieties or fertilization and irrigation practices that avoid slowing crop growth.

Table 15.2 summarizes the cultural, biological, and chemical methods used to effect each of the three processes.
TABLE 15.1 Some features of the crop habitat influencing the spread of crop diseases (after Thresh 1981).

<table>
<thead>
<tr>
<th>SPREAD</th>
<th>Facilitated</th>
<th>Impeded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host susceptibility</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Host longevity</td>
<td>long</td>
<td>short</td>
</tr>
<tr>
<td>Host size</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>Vulnerable plantings</td>
<td>many contiguous</td>
<td>few scattered</td>
</tr>
<tr>
<td>Crop stands</td>
<td>pure</td>
<td>mixed</td>
</tr>
<tr>
<td>Crop spacing</td>
<td>close</td>
<td>wide</td>
</tr>
<tr>
<td>Sources of infection</td>
<td>many</td>
<td>few</td>
</tr>
<tr>
<td></td>
<td>local</td>
<td>distant</td>
</tr>
<tr>
<td></td>
<td>potent</td>
<td>less potent</td>
</tr>
<tr>
<td>Growing season</td>
<td>long</td>
<td>short</td>
</tr>
<tr>
<td></td>
<td>overlapping</td>
<td>distinct</td>
</tr>
<tr>
<td>Winter / dry season</td>
<td>mild</td>
<td>extreme</td>
</tr>
<tr>
<td></td>
<td>short</td>
<td>prolonged</td>
</tr>
</tbody>
</table>

Cultural Control of Plant Diseases

The general strategies that may be taken to decrease disease incidence include avoidance, exclusion or eradication of the pathogen, protection of the host, development of resistant in hosts, and direct therapy of already diseased plants. The methods of biological and cultural control used up to and at the time of crop planting are the most critical for minimizing disease. Controls applied before planting include crop rotation, soil heating through solarization or burning, temporary flooding, soil amendment with large quantities of organic material, and cultivation. Cultivation destroys residues and speeds up their decomposition, but also accelerates colonization by beneficial microorganisms (Cook 1986).

The eradication of wild alternate hosts susceptible to crop disease is at times a useful method, such as in the case of the rust fungi *Puccinia graminis* and *Cranartium ribicola*, whose control requires removal of alternate hosts *Berberis vulgaris* and *Ribes* spp. Methods used at planting include the use of pathogen-free planting material and resistant cultivars.

Genetic diversity offers great potential for genetically controlling pathogens. Genetic diversity can be achieved within fields by planting cultivars with different genes for resistance in different fields across an area, by planting multilines or a mixture of three or four cultivars, each having
TABLE 15.2 General methods of disease control and their epidemiologic effects (after Zadoks and Schein 1979).

<table>
<thead>
<tr>
<th>A. Avoidance of the pathogen</th>
<th>( X _r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Choice of geographic area</td>
<td>( X _r )</td>
</tr>
<tr>
<td>2. Choice of planting site in a local area</td>
<td>( X _r )</td>
</tr>
<tr>
<td>3. Choice of planting date</td>
<td>( X _r )</td>
</tr>
<tr>
<td>4. Use of disease-free planting stock</td>
<td>( X _r )</td>
</tr>
<tr>
<td>5. Modification of cultural practices</td>
<td>( X _r )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Exclusion of the pathogen</th>
<th>( X _r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Treatment of seeds or planting material</td>
<td>( X _r )</td>
</tr>
<tr>
<td>2. Inspection and certification</td>
<td>( X _r )</td>
</tr>
<tr>
<td>3. Exclusion or restriction by plant quarantine</td>
<td>( X _r )</td>
</tr>
<tr>
<td>4. Elimination of insect vectors</td>
<td>( X _r )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Eradication of the pathogen</th>
<th>( X _r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Biological control of plant pathogens</td>
<td>( X _r )</td>
</tr>
<tr>
<td>2. Crop rotation</td>
<td>( X _r )</td>
</tr>
<tr>
<td>3. Removal and destruction of susceptible plants or diseased parts of plants</td>
<td>( X _r )</td>
</tr>
<tr>
<td>a. Roguing</td>
<td>( X _r )</td>
</tr>
<tr>
<td>b. Elimination of alternate hosts and weed hosts</td>
<td>( X _r )</td>
</tr>
<tr>
<td>c. Sanitation</td>
<td>( X _r )</td>
</tr>
<tr>
<td>4. Heat and chemical treatments applied to planting stock</td>
<td>( X _r )</td>
</tr>
<tr>
<td>5. Soil treatments</td>
<td>( X _r )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D. Protection of the plant</th>
<th>( X _r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Spraying or dusting and treatment of plant propagules to protect against infection</td>
<td>( X _r )</td>
</tr>
<tr>
<td>2. Controlling the insect vectors of pathogens</td>
<td>( X _r )</td>
</tr>
<tr>
<td>3. Modification of the environment</td>
<td>( X _r )</td>
</tr>
<tr>
<td>4. Inoculation with a benign virus to protect against a more virulent virus</td>
<td>( X _r )</td>
</tr>
<tr>
<td>5. Modification of nutrition</td>
<td>( X _r )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E. Development of resistant hosts</th>
<th>( X _r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Selection and breeding for resistance</td>
<td>( X _r )</td>
</tr>
<tr>
<td>a. Vertical resistance</td>
<td>( X _r )</td>
</tr>
<tr>
<td>b. Horizontal resistance</td>
<td>( X _r )</td>
</tr>
<tr>
<td>c. Two-dimensional resistance</td>
<td>( X _r )</td>
</tr>
<tr>
<td>d. Population resistance (multiline)</td>
<td>( X _r )</td>
</tr>
<tr>
<td>2. Resistance by chemotherapy</td>
<td>( X _r )</td>
</tr>
<tr>
<td>3. Resistance through nutrition</td>
<td>( X _r )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F. Therapy applied to the diseased plant</th>
<th>( X _r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Chemotherapy</td>
<td>( X _r )</td>
</tr>
<tr>
<td>2. Heat treatment</td>
<td>( X _r )</td>
</tr>
<tr>
<td>3. Surgery</td>
<td>( X _r )</td>
</tr>
</tbody>
</table>

\( X \_r \) = amount of initial inoculum
\( r \) = rate of disease increase
different genes for resistance, or by using cultivars having several genes for resistance within their own genetic makeup (Browning and Frey 1969). Successful control of diseases through introspective within-field diversity has been recorded in wheat (*Puccinia striiformis*), oats (*Puccinia coronata*), and barley (*Erysiphe graminis*) pathosystems (Wolfe 1985).

In Iowa, since 1968, eleven multiline oat cultivars have been introduced, and are grown on about 400,000 ha, so far without loss from crown rust (*P. coronata*). Apparently, the replacement of what in a pure stand would be susceptible plants by resistant ones reduces the amount of susceptible tissue. In addition, the movement of inoculum from one susceptible plant to another is hindered by the presence of intervening resistant plants.

Based on extensive research results, scientists at the National Institute for Agricultural Botany (NIAB) in England created lists of recommended cereal varieties that can be used to select suitable variety mixtures. Table 15.3 illustrates the concept with respect to mildew in spring barley. To use the table, first find the diversification group number for the preferred variety from the NIAB lists and then check that any subsequent varieties chosen are in compatible diversification groups. Even when varietal mixtures are not used, the principles of variety diversification can be applied to the choice of varieties in neighboring fields (Lampkin 1990).

Pyndji and Trutmann (1992) have suggested supplementing farmers' existing mixtures with resistant varieties in order to further reduce the severity of specific diseases. In Africa, this approach led to a significant decrease of angular leaf spot in beans and also avoided indiscriminate displacement of traditional varieties by new varieties.

Genetically controlled resistance is also a major mechanism contributing to the buffering of plant diseases and much work has been conducted on host-plant resistance (Vanderplank 1982). Host-plant resistance can be divided into two types—vertical and horizontal. Vertical resistance is considered to be resistance that is effective against some genotypes of a pathogen species, but not others. Vanderplank noted that vertical resistance often provides very high levels of resistance, or immunity, and is usually inherited monogenically. Vertical resistance presumably correlates with resistance that functions on a gene-for-gene basis with the host. Much emphasis has been given to the use of vertical resistance for disease control because such resistance is simply inherited, easily identified, and often provides high levels of resistance or even immunity against prevalent genotypes of a pathogen. For some diseases, however, widespread use of vertical resistance can rapidly select for virulent genotypes from the pathogen population and render the resistance gene ineffective (Browning and Frey 1969). Therefore, increasing attention has been given to an allegedly different type of resistance that has been variously called general resistance, field resistance, or horizontal resistance. Horizontal resistance is
TABLE 15.3 Varietal diversification scheme to reduce the spread of mildew in spring barley.

<table>
<thead>
<tr>
<th>Diversification Group</th>
<th>1</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>m</td>
<td>m</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>m</td>
<td>m</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>m</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>m</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>m</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>m</td>
<td>+</td>
<td>m</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>m</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>9</td>
<td>+</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>m</td>
<td>+</td>
<td>m</td>
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<td>+</td>
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<tr>
<td>10</td>
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<td>m</td>
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<td>+</td>
<td>+</td>
<td>m</td>
<td>+</td>
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<tr>
<td>11</td>
<td>+</td>
<td>m</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>m</td>
</tr>
</tbody>
</table>

+ = good combination, low risk.  
m = risk of mildew spread

considered to be resistance that is race-nonspecific, and it often provides incomplete resistance (i.e., does not completely suppress pathogen reproduction) and is often quantitatively inherited. Vanderplank (1982) considered horizontal resistance to be more stable than vertical resistance, but he has attributed this stability to a lack of race specificity, and not to a larger number of genes controlling horizontal as compared with vertical resistance.

Choosing the appropriate time and method of planting provides a means to escape pathogens. Planting either earlier or later can permit the host to pass through a vulnerable stage either before or after the pathogen produces inoculum. For example, in England, early potatoes are seldom attacked by Phytophthora infestans, since they are harvested before peak reproduction of the pathogen. Variations in row spacing and depth of planting are other methods that help the crop avoid pathogen inoculum (Palti 1981). Many cropping systems affect disease. If similar crops which may share the same pathogens, do not follow one another, there is a good chance that any inoculum left in the soil will have died from starvation in the absence of its host or it will have been parasitized or lysed by other micro-organisms. In the case of cereals, the removal of the host for one year in a rotation will limit eyespot caused by Pseudocercosporella herpotrichoids. Rotation can also be effected in plantation crops such as banana where incidence of fusarial wilt (Fusarium oxysporum f. sp. cuberie) can be reduced by a 2–3 year break during which rice is grown (Manners 1943). Undersowing wheat or barley with legumes is effective in the control of take-all (Gaeumannomyces graminis). The legume supplies some nitrogen, but after harvesting the cereal and during the autumn the nitrogen is immobilized, and therefore conserved, in the
growing crop and nitrogen starvation decreases the activity of *Gaeumannomyces* (Campbell 1989).

Many of these cultural methods (crop rotation, elimination of alternative hosts, deep plowing of crop refuse, interplanting of unrelated crop types, use of barrier crops) can be incorporated into alternative agricultural production systems; however, their adoption will greatly depend on a number of human, economic, biological, and environmental factors (Table 15.4). Clearly, cultural measures have to be well-adapted to the specific crop/pathogen/environmental interactions of each field, and also have to consider the demands for quick, safe, and economic control of a particular disease.


**Biological Control of Plant Pathogens**

According to Cook and Baker (1983): "Biological control is the reduction of the amount of inoculum or disease-producing activity of a pathogen accomplished by or through one or more organisms other than man." Biological control frequently involves the exploitation of organisms (usually called *antagonists*) in the environment to decrease the capacity of the pathogen to cause disease. The multitude of methods used in biological control can be broadly divided into two groups. Firstly, antagonists can be directly introduced onto or into plant tissue. Secondly, cropping conditions or other factors can be modified in ways known to promote the activities of naturally occurring antagonists. Principles and relevant examples of biological control of plant pathogens are analyzed in Baker and Cook (1974), Cook and Baker (1983), and, more recently, by Campbell (1989).

Biological control includes acting to enhance beneficial microbiology around the plant to suppress the pathogen, or by introducing biological agents in the soil to suppress soil-borne plant pathogens (Papavizas 1973). The enhance-ment approach implies encouragement of known beneficial organisms, naturally existing in the soil, and also creation of deleterious effects on the development of pathogens. The direct approach involves mass introduction of antagonistic microorganisms in soil, with or without a food base, to inactive pathogen propagules, thereby reducing their numbers and adversely affecting infection (Table 15.5). There are many ways in which an antagonist can operate: rapid colonization in advance of the pathogens or subsequent competition may lead to niche exclusion, antibiotics may be produced, or there may be mycoparasitism or the lysis of the pathogen. In addition, some micro-organisms may act simply by making the plant grow better, so that even if disease is present, its symptoms are partly masked. Many ectomycorrhizae, which promote phosphorous uptake in plants, form
TABLE 15.4 Economic, social, biological, and environmental factors affecting prospects for cultural control of crop diseases (Zadoks and Schein 1979).

<table>
<thead>
<tr>
<th>Prospects for Cultural Control</th>
<th>Improve When</th>
<th>Diminish When</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socioeconomic Factors:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop value and level of</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Cost of chemical control,</td>
<td>High (e.g., cereals)</td>
<td>Low</td>
</tr>
<tr>
<td>relative to overall growing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>expenses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chances for regional planning</td>
<td>Good</td>
<td>Bad</td>
</tr>
<tr>
<td>of crops to minimize inoculum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>buildup</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Choices of pre-sowing</td>
<td>Numerous</td>
<td>Few</td>
</tr>
<tr>
<td>practices (soil, season,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>topography)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chances for manipulation</td>
<td>Many (e.g., irrigated</td>
<td>Limited (e.g., dry farming)</td>
</tr>
<tr>
<td>of field conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Educational level of the</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>farmer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pathogen factors:</td>
<td>Splashing</td>
<td>Wind</td>
</tr>
<tr>
<td>Dispersal of inoculum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The wetting period</td>
<td>Long</td>
<td>Short</td>
</tr>
<tr>
<td>needed for infection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The rate of inoculum buildup</td>
<td>Rapid</td>
<td>Slow</td>
</tr>
<tr>
<td>The temperature range for</td>
<td>Narrow</td>
<td>Wide</td>
</tr>
<tr>
<td>development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Susceptibility of</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>overseasoning or dispersal of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>inoculum to heat and drought</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop host factors:</td>
<td>Limited</td>
<td>Plentiful</td>
</tr>
<tr>
<td>Amount of susceptible tissue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>available at any one time</td>
<td>Wide</td>
<td>Narrow</td>
</tr>
<tr>
<td>Range of adaptability to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>various growing conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental factors:</td>
<td>Sub-optimal, at least</td>
<td>Approach the optimum</td>
</tr>
<tr>
<td>Climatic conditions in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>general, in relation to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>growth conditions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 15.5 Examples of antagonists studied in the biological control of plant pathogens (Schroth and Hancock 1985).

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Plant</th>
<th>Plant Pathogen</th>
<th>Antagonist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antibiotic competition/antibiosis</td>
<td>Many hadia</td>
<td>Agrobacterium tumefaciens</td>
<td>Avirulent</td>
</tr>
<tr>
<td></td>
<td>Corn</td>
<td>Fusarium roseum &quot;Graminearum&quot;</td>
<td>Agrobacterium spp.</td>
</tr>
<tr>
<td></td>
<td>Pine</td>
<td>Heterobasidion annosum</td>
<td>Chaetomium globosum</td>
</tr>
<tr>
<td></td>
<td>Various</td>
<td>Various fungi</td>
<td>Peniophora gigantea</td>
</tr>
<tr>
<td></td>
<td>Various</td>
<td>Various fungi</td>
<td>Trichoderma spp.</td>
</tr>
<tr>
<td></td>
<td>Carnation</td>
<td>Fusarium oxysporium f.sp. dianthi</td>
<td>Bacillus subtilis</td>
</tr>
<tr>
<td></td>
<td>Cotton, wheat</td>
<td>Fusarium oxysporium f.sp. var. tritici</td>
<td>Alcaligenes spp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Erwinia amylovora</td>
<td>Pseudomonas solanecarum</td>
</tr>
<tr>
<td></td>
<td>Apple</td>
<td>Erwinia amylovora</td>
<td>Pseudomonas solanecarum</td>
</tr>
<tr>
<td></td>
<td>Tobacco</td>
<td>Pseudomonas solanecarum</td>
<td>Gliocladium spp.</td>
</tr>
<tr>
<td></td>
<td>Many</td>
<td>Various fungi</td>
<td></td>
</tr>
<tr>
<td>Competition for attachment sites</td>
<td>Many hadia</td>
<td>Agrobacterium tumefaciens</td>
<td>Avirulent</td>
</tr>
<tr>
<td></td>
<td>Sweet potato</td>
<td>Fusarium oxysporum f.sp. batatas</td>
<td>Non-pathogenic F. oxysporum</td>
</tr>
<tr>
<td></td>
<td>Cucurbits</td>
<td>Fusarium solani f.sp. Cucurbitae</td>
<td>Squash mosaic virus</td>
</tr>
<tr>
<td>Hyperparasitism</td>
<td>Many hadia</td>
<td>Various fungi</td>
<td>Trichoderma spp.</td>
</tr>
<tr>
<td></td>
<td>Sunflower, beans</td>
<td>Sclerotinia spp.</td>
<td>Coniothyrium minitans</td>
</tr>
<tr>
<td></td>
<td>Lettuce</td>
<td>Sclerotinia spp.</td>
<td>Sporodesmium sclerotivorum</td>
</tr>
<tr>
<td></td>
<td>Sugarbeet</td>
<td>Pythium spp.</td>
<td>Pythium oligandrum</td>
</tr>
<tr>
<td></td>
<td>Cucumber, beans</td>
<td>Rhizoctonia solani</td>
<td>Laetisaria arvalis</td>
</tr>
<tr>
<td></td>
<td>Cucumber</td>
<td>Mildews</td>
<td>Ampelomyces grisqualis</td>
</tr>
<tr>
<td></td>
<td>Rye, other cereals</td>
<td>Ergot</td>
<td>Fusarium roseum &quot;hetero sporium&quot;</td>
</tr>
<tr>
<td>Hypovirulence</td>
<td>Chestnut</td>
<td>Endothia parasitica</td>
<td>Mycovirus</td>
</tr>
<tr>
<td>Parasitism</td>
<td>Soybean</td>
<td>Pseudomonas syringae pv. glycinea</td>
<td>Bdellovibrio bacteriovorus</td>
</tr>
<tr>
<td>Predation</td>
<td>Various fungi</td>
<td></td>
<td>Arachnula impatiens</td>
</tr>
</tbody>
</table>
a physical or chemical barrier to infections preventing pathogens from reaching the root surface. Although the effects of VAM (Vesicular Arbuscular Mycorrhiza) on disease are quite complicated, they are usually beneficial, although some may encourage disease such as Phytophthora root rot of soybean (Table 15.6).

So far, the most promising approach appears to be enhancing biological control agents by changing the microbial equilibrium in the soil or involves the sum of intensified activity of the complex microbial community, including increased liberation of toxic metabolites and competition for nutrients. As microbial activity increases, the expenditure of propagule energy during dormancy presumably increases as a protection mechanism, the net result being an increase in the frequency of propagule exhaustion and death (Baker and Cook 1974).

The use of cover and legume crops, particularly green legumes plowed under, has been especially effective in biologically controlling plant pathogens. A crop of green peas or dry sorghum plowed under before planting cotton in the southwestern United States apparently provides excellent field control of phymatotrichum root rot. The effectiveness of legume cover crops for the control of take-all has been frequently demonstrated. Germinability, and possibly viability, of sclerotia of Typhula idahoensis is greatly reduced in Idaho fields where alfalfa is introduced into the rotation with wheat. Potato scab was prevented from increasing if soybeans were grown annually as a cover crop and incorporated each year before planting potatoes (Baker and Cook 1974).

Leguminous residues are rich in available nitrogen and carbon compounds, and they also supply vitamins and more complex substrates. Biological activity becomes very intense in response to amendments of this kind and may increase fungistasis and propagule lysis. Composts of diverse organic materials have been used to control diseases caused by Phytophthora and Rhizoctonia. The principal controlling factors appear to be the heat of composting as well as antibiotics produced by Trichoderma, Gliocladium, and Pseudomonas. Table 15.7 provides specific examples of augmentation and disease suppression by addition of soil amendments. Table 15.8 gives examples of soil-borne fungal pathogens that can be reduced using green manure. Some examples of soil amendments that reduce nematode populations are presented in Table 15.9.

The literature on soil management practices to enhance existing microbial antagonists is voluminous. Organic amendments are recognized as initiators of two important disease-control processes: increase in dormancy of propagules and their digestion by soil microorganisms (Palti 1981). Organic additions increase the general level of microbial activity and the more microbes that are active, the greater the chances that some of them will be antagonistic to pathogens. This general response to organic matter with a reduction in pathogen inoculum has been used successfully to control
TABLE 15.6 Effects of VA mycorrhizae on soil-borne disease caused by fungi (Schonbeck 1979).

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Host</th>
<th>Effects of Mycorrhizae on Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Olpidium brassicae</em></td>
<td>tobacco</td>
<td>reduction of infection</td>
</tr>
<tr>
<td><em>Pythium ultimum</em></td>
<td>lettuce</td>
<td>none</td>
</tr>
<tr>
<td><em>Pythium ultimum</em></td>
<td>soybean</td>
<td>reduced stunting</td>
</tr>
<tr>
<td><em>Phytophthora megasperma</em></td>
<td>poinsettia</td>
<td>fewer plants killed</td>
</tr>
<tr>
<td><em>Phytophthora palmivora</em></td>
<td>soybean</td>
<td>none</td>
</tr>
<tr>
<td><em>Phytophthora parasitica</em></td>
<td>papaya</td>
<td>reduced stunting</td>
</tr>
<tr>
<td><em>Rhizoctonia solani</em></td>
<td>citrus</td>
<td>reduction of damage</td>
</tr>
<tr>
<td><em>Thielaviopsis basicola</em></td>
<td>poinsettia</td>
<td>reduced stunting</td>
</tr>
<tr>
<td><em>Thielaviopsis basicola</em></td>
<td>tobacco</td>
<td>less stunting, inhibition of</td>
</tr>
<tr>
<td><em>Thielaviopsis basicola</em></td>
<td>alfalfa</td>
<td>chlamydospore production</td>
</tr>
<tr>
<td><em>Cylindrocarpon destructans</em></td>
<td>strawberry</td>
<td>less stunting, reduction of</td>
</tr>
<tr>
<td><em>Cylindrocladium scoparium</em></td>
<td>yellow poplar</td>
<td>infection</td>
</tr>
<tr>
<td><em>Fusarium oxysporum</em></td>
<td>tomato</td>
<td></td>
</tr>
<tr>
<td><em>Fusarium oxysporum</em></td>
<td>cucumber</td>
<td></td>
</tr>
<tr>
<td><em>Phoma terrestris</em></td>
<td>onion</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 15.7 Dry and decayed soil amendments that reduce some diseases caused by soil-borne fungi (after Palti 1981).

<table>
<thead>
<tr>
<th>Crop and Disease</th>
<th>Pathogen</th>
<th>Soil Amendment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potato wilt</td>
<td><em>Verticillium albo-atrum</em></td>
<td>Barley straw</td>
</tr>
<tr>
<td>Potato black scurf</td>
<td><em>Rhizoctonia solani</em></td>
<td>Wheat straw</td>
</tr>
<tr>
<td>Bean root rot</td>
<td><em>Thielaviopsis basicola</em></td>
<td>Oat straw, corn stover, lucerne hay</td>
</tr>
<tr>
<td>Pea root rot</td>
<td><em>Aphanomyces euteiches</em></td>
<td>Crucifer tissues</td>
</tr>
<tr>
<td>Cotton root rot</td>
<td><em>Macrophomina ogasokuba</em></td>
<td>Lucerne meal, barley straw</td>
</tr>
<tr>
<td>Coriander wilt</td>
<td><em>Fusarium oxysporum f.sp. coriander</em></td>
<td>Oil cakes</td>
</tr>
<tr>
<td>Banana wilt</td>
<td><em>F. oxysporum sp. cubense</em></td>
<td>Sugarcane reside, Avocado root rot</td>
</tr>
<tr>
<td>Avocado root rot</td>
<td><em>Phytophthora cinnamoni</em></td>
<td>Lucerne meal</td>
</tr>
<tr>
<td>Root rots of ornamentals</td>
<td><em>Phytophthora, Pythium, Thielaviopsis spp.</em></td>
<td>Composted tree bark</td>
</tr>
</tbody>
</table>

Diseases such as the potato scab (*Streptomyces scabies*), *Phytophthora cinnamoni* rot of avocado, *Phymatotrichum omnivorum* rot, and the sclerotia of *Sclerotium rolfsii* and *Rhizoctonia* (Mukerji et al. 1992). In soils amended with organic materials, propagule germination by the pathogen may not be possible, even in the presence of nutritive mixtures. Evidence suggests that the effect is relatively nonspecific in origin, and other biological control approaches which emphasize inducing resistance in the host by inoculation with non-pathogenic or avirulent
TABLE 15.8 Examples of green manures which reduce some soil-borne fungal pathogens (after Palti 1981).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Disease</th>
<th>Pathogen</th>
<th>Type of Green Manure</th>
<th>Effect on Fungal Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Take-all</td>
<td><em>Gaeumannomyces graminis</em></td>
<td>Rape, pea, or mixed grass legume</td>
<td>Partially reduced</td>
</tr>
<tr>
<td></td>
<td>Eye-spot</td>
<td><em>Pseudocercospora</em> sp.</td>
<td>Partially reduced</td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>Root rot</td>
<td><em>Phymatotrichum omnivorum</em></td>
<td>Pea, <em>Melilotus officinalis</em></td>
<td>Reduced</td>
</tr>
<tr>
<td>Potato</td>
<td>Scab</td>
<td><em>Streptomyces scabies</em></td>
<td>Soybean</td>
<td>Prevented buildup</td>
</tr>
</tbody>
</table>

TABLE 15.9 Soil amendments found to reduce nematode populations (after Palti 1981).

<table>
<thead>
<tr>
<th>Nematode Species</th>
<th>Crop</th>
<th>Soil Amendment Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Meloidogyne incognita</em></td>
<td>Tomato</td>
<td>Sewage sludge, lucerne hay and straw, lesperdeza hay, flax hay</td>
</tr>
<tr>
<td><em>M. javanica</em></td>
<td>Tomato</td>
<td>Sawdust</td>
</tr>
<tr>
<td><em>Heterodera marioni</em></td>
<td>Peach</td>
<td><em>Crotalaria spectabilis</em> in summer, oats in winter</td>
</tr>
<tr>
<td><em>H. tabacum</em></td>
<td>Eggplant</td>
<td>Leaf mold and ammonium sulfate</td>
</tr>
<tr>
<td><em>Pratylenchus penetrans</em></td>
<td></td>
<td>Mycelial residues from production of antibodies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cellulose wates from the paper industry</td>
</tr>
<tr>
<td><em>Hopolaimus tylenchiformis,</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Xipinema americanum</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Helicotylenchus</em> sp.,</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Azidarachta indica</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Tylenchorhynchus</em> sp.,</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Meloidogyne</em> sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Pratylenchus penetrans</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Belonolaimus longicaudatus</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Tylenchulus semipenetrans</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oats, Sudangrass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Activated sewage sludge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Castor pumice (by-product) of castor oil extraction</td>
</tr>
</tbody>
</table>
pathogenic or avirulent strains of a pathogen have been demonstrated in a number of cases, notably in the use of attenuated strains of viruses to control virulent strains. The *Tristeza* virus of citrus crops is controlled in this way, and tomato can be protected from damage by *Tobacco mosaic* virus by prior inoculation with attenuated virus strains. One of the few registered biological control agents which is currently available commercially in the United States and elsewhere involves an avirulent strain of *Agrobacterium radiobacter* (K84), which protects plants against the crown gall pathogen *Agrobacterium tumefaciens* by pre-treatment of wounds with the antagonist. Strain K84 produces a special type of antibiotic or bacteriocin (a high molecular weight protein) that affects only closely related organisms.
Pasture Management to Sustain Agriculture

Bill Murphy

No one would fill a bunk or trench silo with corn or alfalfa ensilage and then turn livestock into it, allowing them to eat what and when they want. Instead, the silage is carefully rationed out according to the needs of livestock, keeping waste of the feed to a minimum.

However, everyone who has grazed animals has turned them out into large pasture areas, allowing them to pick and choose and eat what and when they want. Animals tend to eat plants and parts of plants that they like best, leaving the rest to mature, set seed, and multiply. The most desirable plants such as clovers, are grazed off every time they grow to grazing height. They never have enough time with enough leaf surface for photosynthesis to meet the needs of the plant. As a result, these plants soon wear out and die. With this kind of management, any pasture becomes weedy and unproductive.

In the United States this is not recognized as a management problem; instead, the pastures are blamed. Not many people would try to grow corn, soybeans, wheat, or alfalfa with the same level of attention to cropping management and soil fertility that they use on their pastures. If they did, yields of those crops would not amount to much of anything. Nevertheless, permanent pastures in the United States have traditionally been managed according to the Back-40 Syndrome: don't put anything in, don't expect anything out.

The Back-40 is the run-down permanent pasture (usually 40 acres or 20 ha) where animals are placed in spring and survivors are collected in the fall. If
most survive, the farmer congratulates him/herself for doing a good job of management. Some animals even gain weight if the pasture was understocked. When animals requiring a high level of nutrition, such as milking cows or growing lambs, are grazed with similar management, they aren't very productive.

It is no wonder that farmers in the United States stopped pasturing their animals and went to year-round confinement feeding. The yield of livestock products from pasture was too low to be profitable. The ironic part is that it never was the fault of the pasture. It always resulted from poor management of a forage crop in a pasture situation.

If it were not for New Zealand's highly productive and profitable agriculture, which depends almost entirely on permanent pastures, U.S. farmers probably would have gone on forever, blissfully ignorant of better grazing management techniques and spending much more than they need in producing livestock. New Zealanders produce lamb and dairy products, ship them halfway around the world, and underprice U.S. farmers. They are doing something right. But what?

New Zealand uses grazing management techniques initially defined by Andre Voisin of Normandy, France (Smetham 1973; Voisin 1959, 1960). Voisin taught biochemistry at the National Veterinary School of France and at the Institute of Tropical Veterinary Medicine in Paris. He also was a Laureate Member of France's Academy of Agriculture, and held an Honorary Doctorate degree from the University of Bonn, Germany. Voisin farmed in Normandy, and remained essentially a farmer in his outlook. That is, able to observe and understand natural inter-relationships that often are missed by people not as perceptive and in tune with nature as farmers.

Voisin saw pastures in a unique way. Take care of the pasture plants and soil life, and they will take care of the grazing animals. This is exactly what happens. For example, New Zealand farmers feed almost the same number of cattle as there are dairy cows in the United States, and seven times more sheep (plus 1 million each of deer and goats), but they do it on a pasture area the size of Wisconsin and without grain supplements.

The grazing management method used in New Zealand is referred to as intensive rotational grazing in the United States. This may be misleading, because there's a lot more to it than what that may imply. Voisin called his flexible grazing method *rational grazing* to emphasize the logical, thoughtful management needed in rationing out pasture forage according to the needs of livestock (just as feed is rationed out in confinement feeding), while protecting the plants from the effects of overgrazing and achieving a high level of forage use.

Other terms being used to describe this grazing method include short duration, controlled, planned, and intensive grazing management. Short duration is confusing, since it emphasizes the grazing period in a paddock,
when actually recovery time between grazings is more important. Intensive grazing implies grazing plants to a very short residual, which also might be confusing. Voisin mentioned controlled grazing in his book, but preferred to use a new term to describe his definition of basic elements of the method in a way that would be most useful to farmers.

Recently, Jim Gerrish of the Forage Research Center in Missouri suggested that *management intensive grazing* more accurately describes the method by emphasizing that management is the most important part of grazing, especially under humid temperate conditions (Nation 1992a).

When grazing livestock on rangeland in a brittle environment, it is necessary to use *planned grazing management*. Planned grazing management is Allan Savory's term to describe management intensive grazing when applied to rangeland where management is complicated by drought, soil crusting, wildlife requirements, and public use of the land. It involves planning for specific recovery periods between grazings, monitoring regrowth of individual severely grazed plants, using herd effect to break soil crust to allow water penetration and seedling establishment, wildlife reproduction and feed needs, and hunting seasons. All environments fall somewhere on a continuous scale from brittle to nonbrittle. Unreliable precipitation regardless of volume, and poor distribution of atmospheric moisture through the year characterize brittle environments (Savory 1988).

Whatever the method may be called, make certain that in practice, management includes the key elements of adequate plant recovery time between grazings, and short grazing periods with high stocking density. Whether grazing pasture or rangeland, planning and monitoring certainly must be part of proper management.

Management intensive grazing can be used in North America just as well as in New Zealand where pastures are allowed to reach their full productive potential. The principles are the same, but adjustments are needed to fit local conditions.

*Time of Grazing*

Combining scientific training and experience with diligent observation of livestock in the field, Voisin discovered that time was crucial in grazing management. When Voisin defined the concept of time in grazing management, some important things were realized, especially about overgrazing and stocking density. It became possible to minimize overgrazing and undergrazing. Overgrazing is unrelated to the number of animals present in a pasture and highly related to the time period (how long and when) during which plants are exposed to the animals. If animals remain in any one area for too long and graze regrowth, or if they return to an area before previously grazed plants have recovered, they overgraze plants. For example, 400
cows grazing a 1-ha paddock (that has adequately recovered from a previous grazing) for 12 hours don't overgraze, but one cow grazing the same 1-ha paddock for seven days or more does overgraze.

Voisin's method of planned management intensive grazing interferes as little as possible with the pasture environment, while gently guiding it to benefit the farmer and protecting it from damage by grazing animals. It is a simple method that in essence simply gives pasture plants a chance to photosynthesize and replenish energy reserves after each grazing. Using this method, control what and when livestock eat by dividing pastures into small areas (paddocks) and rotating animals through them. Then ration out pasture forage according to the needs of livestock, allow plants to recover from grazing according to their needs, and keep forage waste to a minimum. The key parts of Voisin's management intensive grazing involve rest or recovery periods between grazings, and the length of time that animals are in a paddock. The following explains terminology and related aspects.

**Terminology**

Following are some useful terms that can help in discussing and understanding what is going on in a pasture:

*Pasture Mass*: total weight of forage per acre, measured to ground level, and expressed as pounds of dry matter per acre (kg DM/ha). When measured before grazing it is *pregrazing pasture mass*; measured after grazing it is *postgrazing or residual pasture mass*.

*Forage Allowance*: total dry weight of forage measured to ground level, expressed per animal or per unit of animal liveweight (e.g., kg DM/cow or kg DM/100 kg liveweight).

*Net Forage*: the amount of forage that actually can be harvested from a pasture (kg DM/ha), either as forage consumed by grazing animals or removed by cutting. Rate of net forage production indicates how much harvestable amount is produced per day (kg DM/ha/day).

*Stocking Rate*: number of livestock carried or supported per acre during a season or part of a season (e.g., 2.8 cows/ha). It is directly related to the amount of feed grown per acre. Stocking rate is important in balancing the feed requirements of livestock with the amount of pasture forage grown on a farm.

*Stocking Density*: the concentrated number of animals grazing a paddock at a given moment is expressed as the number of animals per acre per time period (e.g., 400 cows/ha/12 hours). Stocking density greatly influences pasture plant growth and forage use. Through its effect on herd or flock behavior and level of feeding, it also affects animals' feed conversion efficiency. If the number and/or size of animals remains the same, decreasing paddock size increases stocking density. Increasing numbers and/or size
of animals while paddock size remains constant increases stocking density and vice versa.

**Pasture Sward Dynamics**

To manage pastures well, the biological and ecological bases for management must be understood. Grazing management can then be flexible, based on observation of plants, soil, and animals, and by understanding the ecosystem rather than rigidly following a set schedule of calendar dates that may have very little or nothing to do with pasture plant growth.

Basically, pasture plants must be able to regrow after they have been grazed. That regrowth is powered by energy either from photosynthesis occurring in the remaining leaf surface, or from energy reserves if little or no leaf surface remains. Except for alfalfa (which regrows from energy reserves) and after drought, pasture grasses and legumes regrow mainly from photosynthesis occurring in the remaining leaf surface. Regrowth from energy reserves is slower because it takes time to form enough leaf surface for photosynthesis to function at a high rate. Photosynthesis supplies energy for continued regrowth of the plant and storage of more energy reserves.

Low stocking density and poor forage utilization (lax grazing) result in sparse swards having few or no lower leaves on plants because of shading. When grazed closely, such plants regrow slowly because little or no leaf surface remains. If plants are cut or grazed before enough reserves are stored and few or no lower leaves remain, regrowth will be retarded or will not occur.

**Plant Tissue Flow**

Underlying the simple overview stated above is a complex inter-relationship of plants, temperature, light, soil, organisms, nutrients, water, and livestock that makes the pasture a continually changing (dynamic) ecosystem. In a pasture there is a continuous flow of new plant tissue forming and old tissue disappearing through the processes of aging, death, and decay, or consumption by grazing animals (Figure 16.1). This turnover of tissue can occur very quickly. For example, in perennial ryegrass a new leaf appears on each tiller about every 11 days. Ryegrass plants maintain only three live leaves per tiller, so each leaf lives an average of only 33 days. If leaves are not eaten within their short lifespan, they are lost to the grazing animal (Parsons and Johnson 1986).

Climate, soil fertility, and plant species mainly determine the rate of new herbage formation in a pasture sward. Grazing management can influence this rate by maintaining as green and leafy a sward as possible, so photosynthesis can occur continually, including immediately after grazing when the
plant residue is very short in stature. Sparse, stemmy, yellow postgrazing plant residue with little green leaf surface area remaining, such as occurs when plants have been allowed to grow too tall, takes longer to reach a maximum rate of new herbage formation than does a dense, leafy, green residual.

**Plant Regrowth Curve**

The regrowth curve (Figure 16.2) of plants is S-shaped and has three stages:

1. Early period of slow growth
2. Middle period of rapid growth
3. Final period of slow growth

In the first growth of spring or after being grazed or cut off anytime in the season, plants have limited leaf surface area and only grow slowly. As leaf surface develops and light interception increases, in full sunlight pasture plant growth increases rapidly, then gradually slows as pasture mass and shading increase (Voisin 1959). The rate of new plant growth reaches a maximum at a pasture mass of about 900 to 1,200 kg DM/ha in dense, leafy swards grazed by sheep. Pasture grazed by cattle is less dense and more clumpy, with more erect tillers and leaves than sheep or goat pasture.

![Plant Regrowth Curve Diagram](image)

**FIGURE 16.1** Influence of pasture mass on rates of new plant growth, net forage production, and forage loss through death, decay, and disappearance (Adapted from Korte, Chu, and Field 1987).
Because less light is intercepted, pastures need more leaf surface area and a pasture mass of 2,500 to 3,000 kg DM/ha to reach maximum growth rate.

**Net Forage Production**

After grazing, the rate of net forage production increases rapidly as plant growth and pasture mass increase. When high levels of pasture mass are reached, net forage production decreases as pasture mass continues to increase. This decrease reflects the smaller proportion of new plant growth being harvested, as more forage is lost through death and decay from shading of lower plant parts and low-growing plants such as white clover.

Shaded plant parts continue to respire, but without light they cannot photosynthesize, so until they die they draw energy from parts exposed to the sun. This is a direct loss to a pasture's productivity and is the reason why swards must be kept below 15 to 20 cm tall.

Sooner or later as pasture mass continues to accumulate under poor or very lax grazing management, net forage production becomes zero (i.e., all of the forage rots and animals will not eat it), and pasture mass cannot increase due to shaded conditions within the sward. There is a range of pasture mass over which
net forage production remains high. The rate of net forage production drops markedly at extremely high (3,400–4,500 kg DM/ha) and low (400–700 kg DM/ha) levels of pasture mass (Figure 16.1) (Bircham and Korte 1984, Parsons and Johnson 1986).

**Recovery Periods**

In addition to variation of the plant regrowth curve, plant growth rate also differs within the season. One of the main rules of Voisin management intensive grazing is that recovery periods between grazings must vary according to changes in plant growth rates, which reflect changes in growth. Growth through June is about twice as fast as it is August through September, and July is a transition time between the two. This means that recovery periods between grazings must be about twice as long in August-September as they are in May-June. Of course, plant growth rates vary within regions, seasons and prevailing climatic conditions. (Figure 16.2)

Productivity of plants and the amount of forage available to animals entering a paddock equals the daily amount of plant regrowth per acre (pasture mass) that has accumulated since the last time the paddock was grazed. Figure 16.2 shows that if the recovery period is cut to half of the optimum period, forage accumulation is reduced about two-thirds. If the recovery period is shortened even more, forage accumulation may drop to only 10% of the pasture mass accumulated during the optimum recovery period. This short recovery period corresponds to what happens when pastures are continuously grazed. Desirable plants are grazed off every time they grow tall enough to be grasped by the animals' mouths, or about every seven days. If recovery periods are longer than the optimum, pasture mass increases, but the increase is due mainly to more fiber, which lowers the feeding value of the forage.

Basic recovery period guidelines are helpful for planning and using management intensive grazing. With experience, adjustments can be made to better suit local conditions and pasture plant communities. For example, in the Champlain Valley of Vermont it was found that recovery periods work well for Kentucky bluegrass-orchardgrass-timothy-quackgrass-white clover pasture:

1. 12 to 15 days in late April to early May
2. 18 days by May 31
3. 24 days by July 1
4. 30 days by August 1
5. 36 days by September 1
6. 42 days by October 1
Recovery periods needed in other climatic zones or for other pasture swards (e.g., grass-alfalfa) can be determined by taking into account what is known about the plants' carbohydrate reserve cycles, experimenting with different periods, and observing the effects of different pre- and postgrazing pasture masses on plant regrowth rates.

**Spring-to-Autumn Recovery Periods**

An important question to address is: How can the recovery periods be adjusted during the season to be about twice as long in the autumn as in the spring? There are three practical ways for doing this (see further discussion elsewhere under Spring Management):

1. About one-half or more of the pasture area can be set aside from grazing in the spring (or other periods of rapid growth) and machine-harvested because too much forage is produced in May-June. This means that only about one-half or less of the total pasture area is grazed in May, June, and part of July.

   Using management intensive grazing at least doubles or triples plant productivity, creating forage needing machine-harvest from areas where surplus forage probably has not been harvested before. If the pastures are mainly on rough land, set aside the most level areas so machinery can easily be used to harvest the excess forage. Prepare for the increase in forage production that will occur, otherwise the pasture will not be grazed properly and its full potential will be unrealized. After surplus forage has been harvested, allow the areas to recover until an adequate pasture mass has accumulated. Divide them into paddocks and include them in the rotation. This increases the area available for grazing and automatically lengthens recovery periods.

   For example, on the Hanson's farm in Vermont, 60 lactating Holsteins and 15 dry cows and heifers were fed on six ha of pasture from April 29 to about June 15. Total pasture size is 20 ha. In late May, the Hansons harvested and ensiled surplus forage from the remaining 14 ha of pasture. In June sixth ha of the machine-harvested land was brought into the grazing rotation. In July a second crop of forage as hay was harvested from the other eight ha. In September all 20 has were included in the rotation. Cows grazed until mid-October; heifers and dry cows grazed until about November 1.

2. Graze twice as many animals on the total pasture area during May, June, and the first part of July as in the rest of the season. The decrease in animal numbers carried during the second half of the season lengthens recovery periods to about what is needed. This really is the only way to graze a pasture well if it is all rough land that cannot be harvested with machinery. This means that about half of the animals will either have to be fed elsewhere after July 15, or sold.
3. Another way of keeping pasture forage under control during times of rapid excessive growth, especially on land where machine harvesting is not possible, is grazing less close (top-graze) than usual, leaving more post-grazing pasture mass. This means that animals are rotated through paddocks faster than usual, or allowed to graze several or all paddocks at once. The patchy grazing that will occur is not a serious problem when allowed occasionally and can be minimized by grazing two kinds of animals (e.g., sheep and cattle) on the same land, either simultaneously or one behind the other. When plant growth rate decreases, slow the rotation and return to grazing one paddock at a time.

*Adjusting Recovery Periods*

Recovery periods are, of course, based on observation of plant regrowth and pasture mass. Under conditions that stress plants, such as drought or cold, longer recovery periods are needed. If conditions are more favorable (e.g., warm, moist) than usual for plant growth, less recovery time may be needed.

For example, depending on the animals and their production levels and nutritional needs, swards of Kentucky bluegrass, orchardgrass, timothy, quackgrass, and white clover are allowed to accumulate pregrazing pasture masses of 2,350 to 2,500 kg DM/ha for sheep (about 10 cm tall), and 2,350 to 2,900 kg DM/ha for dairy cows (15 to 20 cm tall) in each rotation, before animals are turned in. Producing animals are removed from paddocks when swards are grazed down to 1,400 to 1,600 kg DM/ha (5 to 8 cm tall). Following groups of dry ewes or dry cows and heifers graze down to 1,100 to 1,400 kg DM/ha (2.5 to 5 cm tall). These pre- and postgrazing masses are target averages; parts of the sward in a paddock will be either above or below these levels (Holmes et al. 1984).

More dense grass-legume mixtures, such as perennial ryegrass-white clover, can accumulate more pregrazing mass (e.g. 3,000-3,300 kg DM/ha) without damaging the sward and decreasing forage consumption. This is because they are still short enough for ease of grazing and for light to reach deeply even at high levels of pregrazing mass.

If the length of time needed to graze a paddock to the required residual pasture mass decreases, the recovery periods for the next paddocks will also be shortened if animals are moved sooner than planned. If recovery periods begin to shorten by even 12 hours in any rotation, it is a warning signal that plant growth has slowed for some reason.

For example, around June 20, recovery periods, which had been 22 days, begin to shorten by 12 hours in each paddock. Carefully check the pasture mass in the animals' next paddocks. If the plants have not regrown enough
in the next paddock, slow the movement of animals through the rotation to allow plants more recovery time. This is accomplished by:

- Increasing the pasture area and number of paddocks available for grazing
- Removing all animals from the pasture and feeding them elsewhere
- Feeding the animals hay or other forage in paddocks until enough pasture mass accumulates (2,350 to 2,700 kg DM/ha) and recovery periods are adequate

Any time hay, greenchop, or silage is fed to animals, including during the winter, do it on different areas of the pasture. If possible, feed on a different area every day. This improves the pasture soil fertility from the added manure, urine, and wasted forage, saves the time and expense of cleaning up and spreading manure, and adds new forage seeds to the pasture.

Another way to increase recovery periods early in the season is to graze areas that had been set aside for machine harvesting, even though the surplus forage has not been cut yet. The animals will not like having to graze tall, more mature plants, after being accustomed to grazing short immature plants, and they will waste a lot of forage. To prevent waste, give them narrow strips of forage about three meters wide, or only enough for 12 to 24 hours. Hold the animals in the strips until they eat most of the forage. Then if possible mow each strip so that they can eat the remaining forage before giving them another strip. It is hard for ruminants to bite off stemmy plant parts, so help them by mowing the plants in this situation.

Animals needing high levels of nutrition (e.g., milking cows, sheep, or goat; growing lambs) cannot be forced to graze this more mature forage completely without reducing their production. Do not force animals with high nutritional needs to graze it as closely. Mow the area that is used for grazing while increasing recovery periods at least once, either in every strip or as soon as the livestock are removed from the area. Mowing cuts the uneaten stems and evens plant growth for grazing in the next rotation.

If recovery periods must be increased later in a season, animals can graze hayland aftermath, Sudan grass, millet, or other crops seeded for this purpose. Green chop or surplus forage harvested earlier from the pasture can also be fed. Remember to feed machine-harvested forage in different areas of the paddock or paddocks if possible.

If plants in the next paddocks to be grazed do not recover enough, less forage is available, and consequently, the movement of animals accelerates through the rotation at a time when it should be slowing down. Voisin (1959) referred to this faster movement of animals as untoward acceleration. Quite suddenly the plants become exhausted, stop growing, and there is no more forage to graze.
Watch the plant regrowth and pasture mass. They are the best indicators of plant condition. Movement of animals among paddocks must always be based on observation of plant regrowth and pasture mass. By meeting this need for adequate recovery time between grazings, pastures can be grazed for most of the year, especially with autumn stockpiling of forage.

**Periods of Stay and Occupation**

The length of time that each group of animals is in a paddock per rotation is called the *period of stay*. The total time that all groups of animals occupy a paddock in any one rotation is called the *period of occupation*. When only one group of animals grazes a paddock system, the period of stay equals the period of occupation. If two groups graze, their total periods of stay equal the occupation period.

When plants are grazed off, they can regrow tall enough to be grazed again in the same rotation if the occupation period is not too long. Periods of stay or occupation must be short enough to prevent grazing of regrowth. In the northeastern and north central United States, plant regrowth may be tall enough to be grazed again after about six days in May-June and 12 days in August-September. Although most plants take 12 days in August-September to regrow to grazing height, some continue to regrow tall enough to be grazed after only six days. For that reason, periods of occupation should never be longer than six days to prevent grazing of regrowth in the same rotation, and actually two days or less for best results.

Periods of stay for any one group of animals should be no longer than three days, giving total occupation periods of six days for two groups of animals. This is due to the fact that the longer animals are in a paddock, the less palatable the remaining forage becomes, and the more time and energy they spend searching for desirable feed. Periods of stay of two days or less if animals are grazed as one group, and one day or less for each of two groups, giving total occupation periods of two days or less, are better than longer periods of stay and occupation.

In practice, the shorter the periods of stay and occupation, the better the conditions are for optimum plant and animal production. Milking, growing, and fattening animals should not be in a paddock for longer than two days per rotation anytime in the season in order to keep them on a consistently high level of nutrition. Milking cows, sheep, and goats produce the most milk if they are given a fresh paddock after every milking. Not only is the forage of higher quality and grazed more uniformly than with less frequent moves to fresh paddocks, but milking animals let their milk down better, anticipating that they are going to a fresh paddock as soon as they are finished being milked. Growing and fattening animals, such as lamb and beef, also gain weight most rapidly if given a fresh paddock every 12 or 24 hours.
Paddocks must be small enough so that all of the forage in each paddock is grazed completely and uniformly within each occupation period. Occupation periods may need to change because plant growing conditions vary during the season, and the amount of available forage changes.

- Lengthening occupation periods, and pregrazing pasture masses consistently above 3,000 to 3,500 kg DM/ha indicate that surplus forage is available. When that happens, some paddocks should be removed from the rotation and machine-harvested, to keep the pasture well grazed to maintain forage quality, sward density, and plant regrowth potential. An alternative is to move animals through the rotation quicker, grazing less closely until the rate of plant regrowth slows.

- Shortening occupation periods and pregrazing pasture masses below about 2,200 to 2,500 kg DM/ha indicates that plant growth rates have slowed and not enough forage is accumulating. In this case more paddocks and pasture areas are needed.

For example, if animals do not eat enough to keep up with the rapidly growing plants in May and June, remove paddocks from the rotation and cut the forage for hay or silage. Suppose that in the first rotation of the season animals occupy paddocks for two days, eating all of the forage available in each paddock within that time. After they have grazed six or seven paddocks, move them to the first paddock that was grazed and start the second rotation. Leave the rest of the pasture area for machine harvesting.

(Return animals to the first paddock only if the plants in it have regrown to at least 10 cm tall and have a fully developed green color. Never allow animals to graze forage that is so young that it is still yellow. Grazing young yellow plants has a similar effect on animals that eating green apples has on people. Grazing plants that are too immature also may result in the plants growing poorly during the rest of the season.)

Recovery periods and occupation periods should work together so that the forage is at the right pasture mass or height when animals are turned into a paddock. When animals enter a paddock, plants should be about 15 cm tall (2,350–2,700 kg DM/ha pasture mass) for cattle or horses, and eight to 10 cm tall (2,350–2,700 kg DM/ha pasture mass) for sheep, goats, pigs, or poultry.

When animals leave a paddock, ideally all or most plants are grazed down to about 2.5 to 5 cm from the soil surface (1,100 to 1,400 kg DM/ha pasture mass). "Ideally" presumes that the animals will graze closely and uniformly. However, their natural inclination is to eat the most palatable forage and leave the rest, especially forage close their own manure.

Depending on plant species and local environment, postgrazing plant heights and pasture masses may need to be greater. Usually the taller the remaining plants are when animals are removed from a paddock, the more selective and uneven the grazing has been. In the early stages of pasture improvement, it is very difficult to have animals graze closer than five cm
from the soil surface because of stubble and matted plant parts from previous years of poor forage utilization.

It always will be difficult to get animals to graze closely in areas that have been machine-harvested, probably because the dry fibrous stubble remaining after mowing pricks their mouths. One way to avoid leaving stubble is to machine harvest surplus forage twice, or every time the sward reaches about 25 cm tall, rather than once when the sward is 45 or more centimeters tall. Two or more immature harvests result in leafier, higher quality hay or silage, and less loss of low-growing plants from shading. Of course, if drying early cut forage is difficult in your area, there may be only one late harvest. One way to delay surplus forage harvests until better drying conditions exist, is to graze surplus areas in the first rotation, then set them aside for later cutting(s).

Animals with high nutritional needs (e.g., milking cows, sheep, or goats) should not graze forage down to 2.5 cm (1,000 to 1,200 kg DM/ha postgrazing pasture mass) from the soil surface, unless the sward is very dense and leafy because their production may be lowered. This is why it is best to follow producing animals with animals having lower nutritional needs (e.g., dry cows, heifers, dry ewes) to graze paddocks down closely (discussed below).

If for some reason two groups of animals cannot be grazed, do not force producing animals to graze down to less than five cm unless some production loss is acceptable. If the pasture can be mowed, producing animals can be allowed to graze less closely, and the pasture can be mowed after each grazing, or periodically during the season. However, this is a compromise because while the animal production remains high, the pasture will not reach its full potential, which ultimately would have resulted in higher levels of animal production. Mowing also takes time, costs money, and burns fuel.

Just as pastures must be protected from overgrazing by using short occupation periods, they should also not be undergrazed. Any plants that are not grazed in one rotation will not be grazed again that season unless they are clipped. It saves time and money, and net forage production increases if the animals graze as uniformly as possible down to one to two inches from the soil surface.

**Stocking Rate and Density**

High stocking density, coupled with quick, close grazing of a paddock and removal of animals until plants recover simulates what happened under natural conditions of regeneration. In the past, large migrating herds of grazing animals grouped closely due to predators and would move through an area eating and trampling plants and disturbing the soil. Their passage broke up plant residues and returned them to the soil to be decomposed. Disturbing the soil allowed seedlings to establish and water to penetrate.
Large amounts of manure left behind provided nutrients for plant regrowth. By the time the herd returned the plants had recovered and were ready to be grazed again. Pasture and range plants evolved under this kind of treatment and require it for best growth. This is the reason underlying why management intensive grazing has such beneficial effects on pasture.

It follows that stocking rate and density greatly affect pasture forage use and net forage production. Increases in stocking rate and density always reduce the amount of pasture forage that is wasted, thereby increasing the efficiency of forage use and net forage production.

On the most intensively managed and efficient farms, for example, livestock eat 80 to 90 percent of forage available to them during the season. On less well managed farms, half of the forage produced may not be eaten, mainly because of low stocking rate and density. Wasting pasture forage prevents high levels of plant and animal production per acre.

Increasing stocking rate and density results in pastures being grazed more intensively during most of the season. Benefits of intensive grazing include less dead and dying herbage in the pasture (i.e., net forage production goes up), better forage digestibility, and more white clover and tillering of grasses in the sward.

Of course, when the stocking rate on the farm is increased, more livestock graze per acre and per ton of pasture forage produced. Less pasture will be wasted, however, eventually the stocking rate could be increased to where the amount of forage eaten per animal decreases and the animal production level will consequently decline. It is relatively simple to estimate the stocking rate based on animal energy and dry matter intake needs and pasture forage production. Pasture stocking rates generally range from 1.7 to 4.4 animal units per hectare (1 animal unit = 500 kg live-weight).

Stocking density depends on how much forage is available to animals in a paddock, how much they are to eat, and how long they will be in the paddock. Paddock size and stocking density should combine so that animals do not have to be moved more frequently than twice a day, or less frequently than every six days, as discussed previously. Keep in mind that more intensive management produces the highest pasture and animal yields. Stocking densities generally range from about 60 to 500 animal units per hectare per occupation period of a paddock, depending on management.

Forage Allowance

Livestock must be offered amounts of pasture forage that are about two to four times more than what they will eat, depending on the animals' production level and nutritional needs. This is to ensure that they are able to eat as much as they possibly can. For example, if a milking cow needs to eat 15 kg DM/day, she must be offered a forage allowance of 35 to 50 kg DM/day. She will leave 40 to
60 percent of the amount offered uneaten as post-grazing pasture mass. Therefore, livestock that need to eat large quantities of forage must be allowed to leave relatively large amounts of postgrazing pasture mass (1,350 to 1,700 kg DM/ha). Animals with low nutritional and dry matter intake requirements can be given a forage allowance that requires them to graze to a lower postgrazing pasture mass (1,100 kg DM/ha) (Holmes et al. 1984, Sheath et al. 1987).

**Sward Measurements**

In addition to understanding the biological and ecological reasons for management intensive grazing, one must be able to estimate the amount of forage present in a sward before and after grazing. It is helpful to discuss sward measurements before getting into the other details (Frame 1981).

**Plant Height, Density, and Pasture Mass.** Both plant height and density are combined in estimating pasture mass. Pasture mass is useful for predicting plant and livestock performance for a particular combination of plant composition in the pasture and at a particular time during the grazing season.

Pasture mass interrelates with forage quality and palatability in affecting productivity of grazing livestock. A high pregrazing pasture mass, over 3,000 to 3,300 kg DM/ha (25–30 cm tall), occurs with low stocking density or infrequent grazing. These high levels of pasture mass can quickly result in decreased forage quality, patches of rank, low-quality uneaten forage, a layer of dead and decaying plant material at the base of the sward, more upright growing plants, patches with no live tillers, death of low-growing legumes, and a shift to undesirable plant species.

For maximum plant and animal production, pasture mass generally should fluctuate between 1,100 to 1,200 (postgrazing) and no more than 3,000 (pregrazing) kg DM/ha, depending on the kind of livestock. Occasional close grazings down to 900 to 1,100 kg DM/ha are needed to maintain high forage quality and desirable sward composition.

The main objective of management intensive grazing is to keep pasture plants within the steep part of their growth curve, so that the rate of new plant growth always remains high (Figure 16.1). If kept within the steep part of the curve, regrowth occurs rapidly after plants are grazed. If postgrazing pasture mass reaches less than 900 kg DM/ha, plants have little leaf surface and are then in the low part of the curve. Regrowth occurs slowly until adequate leaf surface develops. For this reason, pre- and postgrazing pasture masses of each paddock must be estimated for deciding when to move animals in and out of paddocks.

Pasture mass is usually estimated visually or by measuring plant height (sward surface height). Sward height measurements or estimates must be calibrated against actual measurements of the forage present in an area. Sward height affects plant growth and death through shading and,
consequently, influences net forage production. Sward height also affects forage intake and performance of grazing livestock.

For example, maximum utilization of perennial ryegrass-white clover by grazing livestock occurs when swards are maintained at four to six cm tall for sheep, and 8 to 10 cm tall for cattle. For other cool-season grasses (e.g., Kentucky bluegrass, orchardgrass) combined with white clover, best pre-grazing sward surface heights appear to be eight to 10 cm tall for sheep, and 10 to 15 cm tall for cattle. Optimum postgrazing sward heights are 2.5 cm tall for low-growing grasses (e.g., perennial ryegrass, Kentucky bluegrass), and five cm for tall-growing grasses (e.g., orchardgrass, timothy, bromegrass).

Using sward height to guide grazing management actually is not completely satisfactory, however, because it does not take into account variations in plant species and density. For uniform swards, such as nitrogen-fertilized perennial ryegrass growing under uniform conditions, sward height correlates closely with plant density and pasture mass. But sward height measurements may be misleading for estimating the pasture mass of complex swards that contain several grass species, pasture masses that depend on a legume for nitrogen, and pasture masses that grow under variable conditions such as in most of the northern United States.

Since plant density is more difficult to estimate than plant height, visually estimating pasture mass requires experience and some actual measurements of the forage to calibrate visual estimates. Visual density and height estimates may be checked against the actual total amount of forage present, by first estimating the pasture mass in kg DM/ha and measuring plant height within several measured 0.1- x 1-meter areas. Then cut the forage within the areas at the soil surface and place the forage from each area in a paper bag with estimates noted on them. Dry the samples in an oven at about 70 C for one day and weigh the dry forage. Convert the dry weights to kg DM/ha by multiplying each dry sample weight by 100,000. Compare estimates to the actual amount of forage present.

Easier and more accurate ways of estimating pasture mass, especially in complex swards, are to take about 30 readings throughout a paddock with a pasture bulk height plate or with an electronic capacitance meter, both of which take plant density and height into account.

Rayburn (1988) developed a pasture bulk height plate that is very inexpensive and simple to make and use. Purchase a 45.7-cm square piece of 0.6-cm thick acrylic plastic and a meter stick at a hardware store. Cut a 4-cm diameter hole in the center of the plastic square. (Cutting the hole is the most difficult part, because the plastic tends to melt back together. Try to have someone cut the hole at the hardware store.) Attach a 0.3- x 6-cm bolt through a hole in the lower end of the meter stick, to pick up and carry the plastic plate easily while walking around the paddocks. Insert the yardstick through the hole in the plastic plate and it is finished.
Begin taking readings near one corner of a paddock in an area that will be grazed. Always estimate pasture mass in representative grazing areas, not in rejected forage areas near manure. Gently lower the flat side of the plate with the upright yardstick onto the sward. Push the yardstick down until it just touches the soil, and allow the plate to settle by its own weight. Then bend over and look across the top surface of the plate to read the ruler measurement of forage bulk height. Record the reading to the nearest 0.5 cm on a paper or on a calculator that adds and keeps a track of total number of entries. After a total of about 30 readings taken by zig-zagging across the paddock, calculate the average forage bulk height. If the sward is composed of white clover and grasses such as Kentucky bluegrass, orchardgrass, timothy, bromegrass, and quackgrass, multiply the average bulk height by 484 to estimate kg DM/ha.

For best results the plate should be calibrated to the number of pounds of forage dry matter per acre corresponding to the bulk height readings of the swards. To do this, make a wire frame that just fits over the plate. At several sample locations in the paddocks place the wire frame over the plate after taking and recording a bulk height reading and remove the plate. Then arrange the plants so that the wire frame lays flat on the soil surface. Plants rooted within the frame should be in the frame, and plants rooted outside should be outside of the frame. Then cut all of the plants within the frame at ground level with a scissors or a battery powered lawn edger. Place the plant material in a paper bag, and note paddock number, date, and bulk height reading on the bag. Dry the samples in an oven at about 70 C for at least 24 hours. Then weigh the samples and multiply the dry weights by 47.8 to get kg DM/ha.

Graph the values, with inches of bulk height on the X-axis and pounds of dry matter per acre on the Y-axis. Future bulk height readings can be compared to the graph to estimate dry matter per hectare.

Another way of estimating pasture mass is with a computerized capacitance meter that uses changes in electrical capacitance resulting from different plant surface areas, to measure pasture mass (e.g., Pasture Probe, Pasture Gauge) (Fletcher 1982). With a capacitance meter, one can accurately determine when paddocks are ready to be grazed, when animals should be removed from paddocks, and daily and seasonal forage yield of each paddock and the entire pasture.

**Dividing the Animals**

The simplest way to graze is to include all animals in one group. Having the animals all in one group also produces the highest stocking density. Although only one source of water is needed when animals graze as one group, ideally drinking water should be provided in all paddocks, so that the animals, their manure and urine remain in the paddocks being grazed. Also, if drinking water
is always readily available in paddocks, animals do not waste energy walking to and from the water source.

A more efficient way is to divide animals into groups according to their production levels and nutritional needs at different physiological states. This allows close matching of pasture feeding values with animal needs. For example, a dairy herd can be divided into two groups; milking animals and dry animals and young stock. A sheep flock or beef herd can be divided into two groups, weaned animals and dry mothers. The groups of animals can be handled in two ways:

1. Each group can be grazed in separate cells. (A cell is an area of land planned for grazing management as one unit, to be subdivided into paddocks to ensure adequate timing of grazing and recovery periods.) Animals with the highest nutritional requirements (e.g., milking cows, sheep, and goats, growing lambs or stocker cattle) are grazed on the best pasture available. Other animals (dry cows and heifers, dry does and kids, ewes) are grazed in a separate cell on lower-quality pasture that is being improved. An advantage of this method is that only one source of water is needed in each cell, although providing water in all paddocks is preferable. Another advantage is that parasites are not easily passed from older animals to young ones. For producing or growing animals, paddocks should be small enough so that all forage is eaten in each paddock in two days or less (12 to 24 hours is best). Occupation periods for the animals at lower levels of nutrition can be six days or less, but the animals and the pastures will do better if two-day (or less) periods of occupation are used also.

2. Both groups graze within the same cell. Animals having the highest nutritional needs are turned into a paddock first so they can eat the best forage quickly. They should not be left in a paddock for more than two days, because after that time they have to work too hard to meet their nutritional needs (12- to 24-hour periods of stay are best). After the first group is removed from a paddock, the second group follows to dean up the remaining forage, which has a lower feeding value than the forage that was grazed first. Paddocks must be small enough so that the combined periods of stay of the two groups are less than six days (two days or less is best).

When two groups of animals graze within the same cell, all paddocks must have a source of drinking water, because at least one of the groups must stay in its paddock to keep the groups separate.

Number of Paddocks

When planning grazing management, estimate how many paddocks will be required to ensure adequate recovery periods between grazings. The number of paddocks needed depends on recovery periods, stay or occupation
periods of animals in each paddock in each rotation, and number of groups grazing (Table 16.1).

Since shorter occupation periods favor higher plant and animal yields, the more paddocks one has up to a certain point, the more productive the pasture tends to be. In deciding how many paddocks to build, consider topography and soil fertility of the pastureland, pasture sward botanical composition and its potential yielding ability, maximum recovery periods likely to be needed in the area, the livestock, fencing costs, and economics.

1. Estimate the recovery period likely to be needed during the time of slowest plant growth in the grazing season. This may range from less than 36 to more than 100 days, depending on conditions. For example, while 36 to 42 days' recovery time are adequate for late summer and fall grazing in the northeastern United States, a 90-day recovery period may be needed in drier areas of other regions. Remember, these are the total numbers of paddocks needed when pasture plants grow the slowest. During times of fastest growth, such as in May-June in the Northeast, only about one-third to one-half as many paddocks are needed since the rest of the pasture area will be set aside for machine harvesting of excess forage.

2. Estimate how long the periods of occupation will be and decide whether to use one or two groups of animals.

3. Use this equation to calculate the number of paddocks needed:

\[
(\text{Recovery period} + \text{occupation period}) + \text{number of groups} = \text{number of paddocks}
\]

For example, if 36-day recovery periods will be required, and one group of animals is grazed with 12-hour occupation periods, the number of paddocks needed will be: \((36 + 0.5) + 1 = 73\).

If one group grazes with two-day occupation periods, then: \((36 + 2) + 1 = 19\) paddocks needed.

If you divide your animals into two groups and graze within the same cell, just add one more paddock: \((36 + 0.5) + 2 = 74; (36 + 1) + 2 = 38;\) or \((36 + 2) + 2 = 20\).

**TABLE 16.1** An example of the number of paddocks needed for a 36-day recovery period between grazings.

<table>
<thead>
<tr>
<th>Period of Stay for One Group, Days</th>
<th>Total Number of Paddocks Needed</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>One Group</td>
</tr>
<tr>
<td>1/2</td>
<td>73</td>
</tr>
<tr>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
</tr>
</tbody>
</table>
The more paddocks that can be formed to provide adequate recovery periods and short occupation periods, the better. Up to about 30 paddocks, each new division significantly shortens the average occupation period of all paddocks. Beyond that, the gains become less as more paddocks are formed. Do not even attempt to use management intensive grazing with fewer than 10 paddocks because the results will be very disappointing. The more paddocks there are, the more flexibility exists for dealing with changing amounts of forage available during the season. For example, with only six paddocks, if forage production in one of them drops off, the decline would affect one-sixth of the pasture area. In contrast, with 37 paddocks, a problem with one of them only affects one/thirty-seventh of the pasture area.

At this point it may seem that building a lot of paddocks will be too expensive, and that the management required to control grazing will take too much time and effort. Providing detailed information and anticipating questions that have been addressed in this chapter may make the process seem more complicated on paper than it actually is in practice. However, the costs of grazing management when done correctly, will soon be paid back and increase the profitability of the farm. The method requires much less time, labor, and expense than feeding animals in confinement. Due to recent developments in fencing materials, the cost and building of paddocks is surprisingly inexpensive and easy to do.

The most important point of all this is to have enough paddocks to provide the required adequate recovery periods, with the appropriate periods of stay and occupation. The main idea is to graze the sward at the optimum stage of growth for the plants and animals. The plan should be thought of as a starting point upon which to build and that is changed as more experience is gained from observing results, and as the pasture improves. Do not try to force the plants and animals to fit a rigid schedule. Remember that these are guidelines to help develop a management routine of planning, monitoring, controlling, and replanning if necessary.

Paddock Size and Forage Allowance

Decide on the number of paddocks to have, then divide the total pasture area by the number of paddocks to roughly estimate the average area of each paddock. Paddocks do not have to be equal in area, but should produce more or less similar amounts of forage to facilitate moving animals on a fairly regular schedule. For example, pasture areas with fertile soils and good moisture conditions may produce twice as much forage as areas with poor, dry soils. Paddocks in the highly productive areas should then be about half the size of those in the poor areas.
Electric fencing is possible and easy to relocate or subdivide if necessary. For example, as the pasture becomes more productive and the animals cannot eat everything within the occupation period (e.g., 12 hours), simply divide the paddocks in half, in thirds, or whatever it takes to reduce the forage allowance enough.

As stocking density (number of animals confined to a certain area at a given moment) goes up, there is more competition among the animals for feed and less selective grazing. Under heavy stocking density (e.g., 350 to 500 animal units/acre/12 hours), even high-producing dairy cows will graze uniformly and close to the ground. They do best if forage quality is high, forage allowance is adequate, and their rations are correctly balanced with energy, protein, and mineral supplements needed for the desired production level.

Paddock sizes must be adjusted according to the intensity of management desired. The exact paddock area to use depends on how often the animals are to be moved, pasture productivity, numbers, kinds, and sizes of the animals grazing, and their forage needs.

Calculate paddock areas needed to provide the proper amount of forage (forage allowance) from estimated livestock dry matter intake needs and pasture mass relationships. This can be done as frequently as every 12 hours to form portable-fenced paddocks based on daily pasture mass measurements, or only once to estimate paddock size during permanent fence planning.

\[
Paddock \text{ area} = \frac{(\text{No. animals x dry matter intake})(\text{days})}{\text{Pregrazing mass} - \text{postgrazing mass}}
\]

Calculate 3 to 4.5% of average bodyweight for dairy cows (depending on supplementation level), 3% for stocker cattle, 4% for lactating sheep, 4.5% for growing lambs, and 5.5% for lactating goats and growing kids to get a close estimate of what pasture forage dry matter intake will be per animal per day. This assumes that the pasture is well managed and its forage is of good to excellent quality.

For example, a herd of 70 Holsteins requiring 18 kg DM/head/day from pasture (calculated: 3% x average bodyweight of 600 kg), is given a fresh paddock every 12 hours. Pregrazing pasture mass will be 2,900 kg DM/ha, and postgrazing pasture mass will be 1,600 kg DM/ha. The paddock size to provide adequate forage allowance will be:

\[
Paddock \text{ area} = \frac{(70 \text{ cows} \times 18 \text{ lb DM/head/day})(.5 \text{ day})}{2,900 \text{ kg DM/ha} - 1,600 \text{ kg DM/ha}}
\]

\[
Paddock \text{ area} = \frac{70 \times 18 \times 0.5}{1,300} = 0.5 \text{ hectare}
\]
If using a large rectangular paddock of 100 by 3000 meters with permanent perimeter fence, decide what size the subdivisions (breaks) should be:

**Paddock breaks for 70 cows for 12 hours:**

\[
100X = 0.5 \text{ ha} \\
1 \text{ hectare} = 10,000 \text{ square meters} \\
0.5 \text{ hectare} = 5,000 \text{ square meters}
\]

Solve for \(X\), the unknown measurement of the breaks to make:

\[
X = \frac{5,000}{100} = 50
\]

Therefore, the breaks should be \(50 \times 100\) meters/70 cows/12 hours. Check to see if the breaks are the right size from the daily observation of how much forage the cows are leaving behind, how they behave (do they act nervous as if they are hungry, or contented and relaxed like full cows?), and their milk yield. If dry cows and heifers follow milkers, grazing management is easier. If the milkers leave too much forage behind, the followers can eat it and keep the sward in good condition.

The flexibility of portable fencing enables easy machine harvest of surplus forage from small subdivisions or breaks, since break fences can be removed easily. Variable conditions and situations require experimenting with different sizes of paddocks, unless the above measurements and calculations are done.

Paddock size is important, but not nearly as important as being absolutely certain to provide adequate recovery time between grazings.

**Early Spring Management**

At least four problems must be dealt with in the first number of spring rotations:

1. Transition time needed by animals to adapt to eating green forage after months of eating relatively dry feed, to avoid scouring and bloat
2. Keeping grasses in the vegetative growth stage to prevent flowering and seeding, which decreases their feeding value
3. The need to stagger the amount of forage available in paddocks so they do not all need to be grazed at once
4. Pugging of wet soils (not just a spring problem)

**Scouring and Bloat**

Pasture forage in early spring is extremely lush (only about 15% dry matter) and contains very high levels of crude protein (about 30%). If a protein supplement has been fed to dairy cows, stop feeding it or decrease
the level of supplementation. Otherwise the animals have to eliminate excess protein from their bodies and may scour (dysentery). If ammonia is smelled in the barn or milking parlor and cow feces are runny, excess feeding protein supplement is being fed and money lost.

Bloat can occur in pastured animals (mainly cattle) when they graze succulent legumes (alfalfa, red and white clover), especially in spring. Due to a complex interaction of animal, plant, and microbiological factors, a stable foam forms in the rumen. Because of the foam, gas cannot escape. Pressure builds up in the rumen, causing it to swell and press against the lungs, preventing breathing. If not treated quickly, the animal dies.

Precautions are needed to avoid scouring, bloating, and death of your animals, and to allow time for microorganisms in animal digestive tracts to adapt to using lush pasture forage:

1. During at least the first two weeks of spring turnout:
   - Fill animals up with hay before putting them on pasture for a couple of hours late in the morning or early afternoon (first few days);
   - Move to fresh paddocks only when dew or rain has dried off;
   - Always have dry hay available to animals on pasture in case some animals need additional dry fiber;
   - Have water, salt, minerals, and sodium bentonite always available to animals on pasture; and
   - Watch animals closely; call a veterinarian at the first signs of bloating

2. Nitrogen fertilizer applied to the pasture in the spring will result in succulent forage. There is already going to be too much succulent forage in the spring so if a nitrogen fertilizer is applied to the pasture, wait until early summer to boost forage production as needed.

3. Feed antifoaming agents (e.g., poloxalene, Bloat Guard®) or add them to drinking water beginning several days before the animals are first turned out to pasture and continue until they have adjusted to the lush forage.

4. Manage grazing so that the sward contains less than 50 percent clover or alfalfa. This is achieved by allowing greater pregrazing pasture mass with grasses shading the legumes to decrease their amount in the sward.

5. Tendency to bloat seems to be hereditary. The best long-term solution is to cull animals that bloat.

Keeping Grass Vegetative

Cool season grasses reproduce rapidly in the spring. If grasses manage to flower and set seed, their forage production and quality greatly decreases during the rest of the growing season. Therefore, the main management goal in spring is to keep pasture grasses in a vegetative stage. There are several ways of achieving this goal, all requiring one to walk the pasture daily and observe. (Nation 1992 b, c; Nations 1993):
Set Stock (Continuous Graze). Open all paddock gates to allow the animals to top-graze the entire pasture, leaving a high postgrazing mass of about 2,200 kg DM/ha (10–12 cm tall). This lax grazing will result in patches of clumpy pasture that does not look very good, but is much better than allowing much or most of the pasture to get out of control and go to stem and seedhead. When plant growth starts to slow down, begin closing paddock gates to rotate through one paddock or break at a time.

Rotate Fast. To continue grazing rotationally, move animals to fresh paddocks more than once or twice a day. Top-graze all paddocks every 5 days. This lax grazing will also result in clumpy pasture, but will not cause a serious problem. As soon as plant growth rate slows, grazing can become close again, allowing light to reach low-growing plants. The animals will receive excellent nutrition, and production probably will increase—a payoff for the extra work.

Use Big Breaks. To break-graze (subdividing large paddocks) with portable fencing, make large enough breaks so that all of the pasture is top-grazed every five days.

Increase Number of Animals. Bring in extra animals to graze until plant growth slows, under a contract that pays you for their weight gain.

Machine Harvest Surplus Forage. Set aside part of the pasture area for machine harvesting of surplus forage as hay or haylage. If possible, cut it when 25 to 30 cm tall, so low-growing legumes are not shaded out and there is no stubble later to bother grazing animals. Harvested forage at this stage will be very high-quality. Top-grazing the set-aside area once in early spring will shift the surplus to later in the season when the weather is better for making hay (Nation 1993).

Staggered Forage Accumulation

Graze Early. Graze some paddocks a little too early so that others are not grazed way too late. Begin grazing some paddocks when pasture mass reaches 1,600 to 1,800 kg DM/ha (plants are only 5 to 8 cm tall). Make certain that the plants have a fully developed green color in the first paddocks before grazing begins.

Unless grazing is started early in the first paddocks, by the time the animals reach the last ones to be grazed in the first rotation (12 to 20 days later, depending on occupation periods), the forage in them will be too mature, and the animals will not graze them well. This is not as much of a problem if one is willing and able to clip the last few paddocks soon after they are grazed. Otherwise, the forage that is left in the first rotation will be there all season and will decrease the productivity of those paddocks.

Stockpile Autumn Forage. Another way to stagger the amounts of forage available in paddocks is to stockpile (leave ungrazed) forage in the autumn
on part of the pasture. The feeding value of this forage does not decrease much if it is frozen and covered with snow. Grazing can begin very early (e.g., mid-March) on stockpiled areas. Soils at this time of spring will be soft, so keep occupation periods short (e.g., 1-3 days).

**Pugging of Wet Soils**

Wet soil conditions complicate grazing management, but if pugging from animal hooves is not severe, plant production will not decrease at all, and may even increase because short grazing periods with some pugging stimulates pasture plant growth. If pugging is extremely severe, plant production will decrease for a few weeks to a few months, but will eventually be better than before the pugging. Farmers have found these ways of dealing with wet soil conditions that do not severely damage the pasture:

1. Use short grazing periods of only two to three hours during the day and again in the evening. At other times keep animals on a concrete pad, in the barn, or on a well-drained area. Do not leave animals on wet pasture soil overnight. Provide hay, haylage, or silage, and any supplements free choice to animals after they graze, not before. This ensures that the animals are hungry when they are on the pasture, so they can quickly eat their fill. Remove them from the pasture as soon as they stop grazing.

2. Graze the back ends of paddocks first, allowing animals to walk to the back over ungrazed plants.

3. Always backfence so that animals cannot return to areas already grazed.

4. Allocate only the amount of forage needed and the paddock area that contains it for the short grazing periods. This reduces walking and pugging.

5. Allow animals to undergraze during wet weather.

6. Keep the animals moving slowly through the rotation by allocating a little of the pasture area at a time, so that only part of the pasture gets pugged. This is difficult to do in the spring when plant growth rate is very fast, and fast grazing is needed to control the growth and keep the plants vegetative. Later when soils are drier, deal with the pasture areas that got out of control.

7. Graze poorly drained paddocks during drier weather, and well drained paddocks during wet weather.

8. Construct all-weather lanes.

9. Provide more than one entrance to paddocks that allow animals to fan out quickly, distributing themselves throughout the paddock.

10. Use different gates for animals to enter and leave each paddock.

11. Grade paddocks that tend to be wet into humps and hollows to drain surface water quickly into open drains. Leave 10 to 14 meters between hollows. Hollows need to be cleaned every year with a drain spinner.
12. Spread gravel in paddock entrances and around water tanks to prevent mud being carried into paddocks and soiling the forage.

13. Broadcast seed on severely pugged areas immediately after grazing. This is an opportunity to introduce new varieties of grasses and legumes. Birdsfoot trefoil and annual ryegrass reportedly quickly on such areas (Nation 1992a).

**Late Spring Management**

When the weather begins to get hotter with approaching summer (e.g., early June), it may be beneficial to mow the pasture with a mower set high to remove just the stems and seedheads that escaped early spring management. Stems and seedheads bother livestock’s eyes, and make the surrounding forage less palatable and nutritious.

After mowing, apply nitrogen to boost forage accumulation to get more easily through the summer period of plant growth slump. Either apply liquid manure (about 12,000 liters/ha), other manure (composted or uncomposted) pulverized and spread very thinly so that plants are not smothered, or nitrogen fertilizer (about 65 kg nitrogen/ha). Try to apply any of these materials right after animals graze a paddock, and if possible before a rainfall.

**Rotational Sequence**

Paddocks grazed in the same sequence every year will soon have as many different pasture plant populations as there are paddocks. This is because some paddocks will always be grazed too early for certain plants, some will be grazed just right, and others will be grazed too late. The way to distribute the stresses of early and late grazing in the first rotation is to start with a different paddock each year and use the other paddocks in a different sequence, if possible.

During wet spring and fall conditions, graze higher and drier areas to avoid problems with mud and soil pugging. It may be impossible to make much of a change in the sequence of paddocks grazed. Nevertheless, even if only the first grazing each year is alternated between just two paddocks, it is better than not changing the sequence at all.

Later in the season, if the forage in a paddock is ready to be grazed ahead of its time in the sequence, go ahead and graze it. Grazing out of sequence will not damage the plants because their faster growth indicates that conditions in the paddock are more favorable than in other areas of the pasture, and that they have had adequate time to recover under those conditions. Grazing management must be flexible to deal with the ever-changing pasture environment.
Soil Quality and Management

Fred Magdoff

Soil Quality

Most farmers know the difference between a very good soil and a soil with poorer properties. Those soils with naturally better qualities, such as the deep alluvial soils in river valleys, which tend to be of better fertility and water-holding status than surrounding soils, are usually more prized and hence cost more to purchase. Soil health, or quality, refers to the conditions of a wide range of the soil properties. The concept is much broader and encompassing than the narrow definition of soil fertility that is frequently used. For example, traditionally the main concerns of those working on soil fertility have been whether there are sufficient amounts of nutrients (such as nitrogen, phosphorus, and potassium) available to the plant. Soil fertility investigations have also focused on the influence of other soil properties, such as low pH and nutrient availability, but have not covered the full breadth of properties that impact on plant growth.

What exactly is a high quality or healthy soil? It is a soil on which healthy, high yielding, and nutritious crops can be grown with a minimum of adverse impacts on the environment. It is also a soil that provides stability of properties and crop growth and health in the face of varying conditions of natural (mainly weather-related) or human origin. For example, if rainfall is lower or higher than optimum, yields should not be as negatively influenced as on low-quality soils. A high-quality soil should be resilient and resistant to degradation.

The various factors that determine soil quality are essentially those properties that have a major influence on crop growth. Many of these
properties are not primarily soil "fertility" (defined in the narrow sense) issues. For example, the ease with which the surface of a soil develops a "crust" (a thin low permeable layer that is formed when aggregates near the surface break down under the action of rainfall and/or traffic) has an important effect on both crop growth and the environment. Surface crusting is a significant problem for many soils in both tropic and temperate regions (Sumner and Stewart 1992). When surface crusts develop, seedling emergence following germination may be restricted. More importantly, compared to soils with good surface aggregation, lower amounts of water infiltrate into crusted soils resulting in both less water storage for crop use and increased runoff of water and accelerated soil erosion. The sodium and dispersible clay contents and aggregate stability are all properties that influence the susceptibility of a soil to developing a surface crust.

Other properties that affect soil quality are the depth available for root exploration, pH, salinity, cation exchange capacity, mineralizable nitrogen, the presence of plant pathogens, soil microbial biomass, and so on. (Table 17.1). Soils used for agriculture inherit many properties from the natural state. Some of these properties, such as soil texture (the percent of sand, silt, and clay size particles present) and depth to a layer that restricts root growth, can be modified only at such great expense as to make it impractical in most situations. However, almost all of a soil properties are influenced to one degree or another by how the soil is managed and the choice of crops to be grown. Even if the texture is not changed, the droughtiness of a sandy soil or the cloddiness of a clay soil is under a degree of control by human activities.

<table>
<thead>
<tr>
<th>PHYSICAL</th>
<th>CHEMICAL</th>
<th>BIOLOGICAL</th>
</tr>
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<tbody>
<tr>
<td>Water-holding</td>
<td>Nutrient availability</td>
<td>Soil organic matter</td>
</tr>
<tr>
<td>capacity</td>
<td>Infiltration rate</td>
<td>Soil microbial biomass</td>
</tr>
<tr>
<td></td>
<td>Soil depth, horizons</td>
<td>Respiration/biomass (q CO₂)</td>
</tr>
<tr>
<td></td>
<td>Soil texture</td>
<td>Mineralizable (labile) N</td>
</tr>
<tr>
<td></td>
<td>Soil bulk density</td>
<td>labile organic C (0.5-2 mm)</td>
</tr>
<tr>
<td>Aggregate</td>
<td>Cation and anion exchange</td>
<td>Soil respiration</td>
</tr>
<tr>
<td>stability</td>
<td>capacity</td>
<td>Vegetation growth and cover</td>
</tr>
<tr>
<td>Dispersible clay</td>
<td></td>
<td>Abundance of &quot;key&quot; earthworm</td>
</tr>
</tbody>
</table>

Many things can cause the quality of a soil to deteriorate. For example, working a clay soil when it is too wet may cause the breakdown of natural aggregates and lead to a significant decrease in soil tilth. Deterioration of soil quality can also be caused by such things as intensive cropping together with the lack of crop rotations (Ketcheson 1980), allowing soil salinity buildup under irrigation, or allowing organic matter content to drop too low. Deterioration may also be caused by pollution with potentially toxic metals or synthetic organic chemicals. It is clear that it is most efficient to promote practices that avoid degrading soil quality rather than having to deal with remediation of degraded soils.

There is interest in developing a soil quality "index" to help compare different soils. As part of the development of such a method of comparison, it will be necessary to assign relative weights to the various properties that are evaluated as important contributors to the index. How various factors are proposed for weighting is certain to generate a lot of discussion and controversy. At present, there is no accepted system for assessing soil quality and we will have to get along for the foreseeable future without a quantitative index. However, organic matter influences almost all important properties that contribute to soil quality. Thus, it is critical to understand and stress the key role of managing crops and soils for organic matter buildup and maintenance to developing high-quality soils.

The Nature of Soil Organic Matter

There are three different general types of organic matter that occur in soils: (a) the living organisms, (b) active dead organic matter (slightly decomposed or undecomposed, labile), and (c) well-decomposed (humified) relatively stable materials. Each one of these fractions serves important roles in maintaining and improving soil quality. These three different parts that together make up soil organic matter will be discussed separately below.

Soil Organisms

Living soil organic matter is made up of a varied group of organisms. These organisms include the microscopic viruses, bacteria, fungi, and protozoa, small and medium sized arthropods, earthworms, and so on. In general, as organism size increases the population density decreases. For example, there are about 1,014 bacteria, $10^9$ fungi, $10^7$ nematodes and $10^2$ earthworms per m$^2$ (Smil 1991).

It is true that in soils there are disease-causing bacteria and fungi as well as parasitic nematodes and insects. However, the overwhelming number of all groups of soil organisms feed either on crop and other organic residues or on other soil organisms and do not cause problems for plants. In fact, their
activities in helping to cycle nutrients, keep low populations of pests, produce substances that promote the building of soil aggregates, and produce humic substances make the vast majority of soil organisms very important to soil quality.

All organisms need access to a range of elements in available forms as well as energy. Green plants derive their energy from sunlight by the process of photosynthesis, their carbon (the "backbone" of all organic molecules) from carbon dioxide in the atmosphere, oxygen needed for respiration (to recover and utilize the energy stored in organic molecules) also from the atmosphere, and the rest of their nutrients (N, P, K, S, Ca, Mg, Fe, B, Mn, Cu, Mo, Cl, Zn, Co) as well as water ($H_2O$) from the soil. Almost all organisms living below ground derive energy for their living and reproduction from sunlight energy previously stored in green plant tissue. Although organisms also derive individual elements (such as N, K, Mg) for their use, it is their need to get energy which causes them to so thoroughly break down organic molecules.

Organisms occupy various positions within a food web. The concept of a food web is that the organisms within a particular ecosystem are related to an underlying food source and to each other by virtue of their food source(s).

**Primary consumers** are those soil organisms that are the first to utilize crop and other residues as energy materials. Many fungi are early colonizers of plant debris and serve to soften it and make it more available for other organisms to use. Many bacteria are also primary consumers as are sowbugs, nematodes, fly larvae, and so on. Some earthworms are also primary consumers, and the action of their digestive systems serves to macerate and mix the residues with bacteria in their digestive systems so that their casts are readily available for other organisms to continue utilizing. These earthworm casts are much higher in almost every measure of fertility, such as available calcium, potassium and nitrogen, than the surrounding soil. Earthworm burrows are also important in promoting water infiltration into soils during intense rainstorms.

**Secondary consumers** are those organisms that prey upon primary consumers. Protozoa and nematodes are two common feeders on bacteria and fungi. The rates of consumption of bacteria by nematodes can be extremely high (as high as 5,000 cells per minute has been reported) and it is estimated that about 50% of the annual production of fungi and bacteria are consumed during feeding by secondary feeders (Paul and Clark 1989). The presence of active populations of feeders on bacteria and fungi may well help to maintain more diverse populations of these organisms in soils (Habte and Alexander 1978). As protozoa and nematodes feed on bacteria, excess nitrogen is converted to ammonium and excreted to the soil solution and these organisms are thereby significant contributors to the nitrogen cycle. Other secondary consumers include springtails (Collembola) and mites and some beetles.
**Tertiary consumers** include ground beetles, pseudoscorpions, centipedes, and ants. These fauna feed primarily on other soil organisms. Because of their large size and burrowing abilities, some centipedes and ants can help mix and loosen the soil (as do termites, a mound-building primary consumer). While these activities usually promote a better soil structure, neither organism mixes organic residues with soil in the manner of earthworms. Plant roots are also an important aspect of life within the soil. Products derived from photosynthesis above ground are translocated to roots for their own metabolism. Much of the CO$_2$ generated in the soil is from respiration of root cells or respiration of soil organisms that derive most of their energy from photosynthetically produced products translocated to roots. The gelatinous mucigel surrounding young roots provides an ideal place for soil organisms and clay particles to come into close proximity to roots. In addition to the mucigel, sloughed off of root cells and the large number of compounds exuded by roots also make the rhizosphere zone particularly enriched in soil organisms. The rhizosphere commonly contains 10 to 50 times the number of organisms as found in soil at some distance from the root (Paul and Clark 1989).

**Biological Diversity of Soil Organisms**

A primary goal of good crop and soil management should be to create conditions for a highly diverse community of soil organisms. Biological diversity in the soil, just as diversity above ground, is an important part of agroecosystem stability and health. A wide mix of organisms creates a system in which competition for food sources and niches and predator-prey dynamics help to limit populations of disease-causing bacteria and fungi, plant parasitic nematodes, and problem insects. Some of these problem organisms may actually be present in a soil with high biological diversity, but the populations of the various pest organisms will most likely be below that needed to cause significant effects on crops.

Microbial populations are influenced by cropping and residue management. In general, diversity of organisms is decreased and the amount of microbial biomass is decreased by shifting from natural ecosystems to agroecosystems. For example, after 58 years of cropping in the northwestern United States, microbial C represented 2.8% and 2.2% total soil carbon under annual cropping and wheat-fallow compared to 4.3% under grass pasture (Collins et al. 1992). In Peru, there was a dramatic decrease in biological diversity of soil macroflora in intensively cropped soils or secondary forest soils compared to primary forest soils, as approximately 35% to 50% of the taxonomic units were lost (Lavelle and Pahanasi 1989). The decrease in taxonomic units and population densities were not as severe under low-input traditional systems as occurred with intensive high-input practices.
Soil and crop management can influence population dynamics of soil organisms. Complex rotations with a number of different crops, large amounts of different types of crop residues and manures, cover crops, and reduced tillage are all practices that promote a biologically diverse population of soil organisms. The approach of combining the use of a number of different sources of organic materials has been successfully used to convert a soil with a major problem of *Phytophthora* root rot for avocado into a soil that actually suppresses the disease (Cook 1982). Crimson clover grown in the off season between corn crops led to significantly higher populations of a variety of bacteria, greater microbial biomass, and activity of a number of enzymes than without the cover crop (Kirchner et al. 1993). Using mulches or just leaving residues on the soil surface will promote the populations of surface feeding earthworms. Surface residues tend to accentuate the importance of fungi in the decomposition process. Surface residues and cover crops are also good habitat for spiders, which are generalist feeders on insects and may help reduce insect pest populations.

**Active Organic Matter**

The active fraction of dead material consists of fresh residues as well as residues that have been only slightly decomposed. These residues occur in soils as roots and incorporated above-ground residues and they are available for soil organisms to decompose relatively easily. Fresh residues are the most active part of the organic matter, with about 60% to 80% decomposed during the first year.

There has been much interest in recent years in separating various fractions of organic matter by physical procedures—either by density or size differences (Christensen 1992). The most active part of the organic matter appears to occur as particles that are not strongly associated with inorganic minerals. This light fraction, found in greatest abundance in virgin soils and consisting of relatively fresh residues, can easily be separated from the rest of the soil (Janzen et al. 1992). Organic matter associated with sand size minerals is also quite easily decomposed while there is some indication that part of the organic matter associated with clays is mineralized reasonably easily and is an important source of available nitrogen (Christensen 1992).

Under some conditions, such as long-term sod growth, the amount of active organic matter in a soil may be quite large. A study by Cambardella and Elliott (1992) found that close to 40% of the total carbon (or organic matter) was present as particulates under native sod. However, after 20 years of stubble mulch management for a wheat/fallow system only 19% of the organic matter was present in particulate form.
**Well-Decomposed Organic Matter**

The well-decomposed and relatively stable fraction of soil organic matter is usually called humus. Humus is strongly associated with the clay and silt fractions and is present in soil for a long period of time, with mean residence times on the order of hundreds or thousands of years. The organic matter associated with silt size mineral particles appears to be more stable than that associated with clay (Christensen 1992).

Soil humus decomposes fairly slowly, with about 2% to 5% decomposing annually. Humus contains most of organic matter's cation exchange capacity (negative charges that allow retention of certain nutrients such as calcium, magnesium, and potassium).

Although much of the organic matter that decomposes during the year may be reasonably fresh, some organic matter that is relatively stable can be converted into available forms by drying and rewetting and freezing and thawing cycles (Bartlett 1981, Bartlett and James 1980, Birch 1958, Mack 1963, Soulides and Allison 1961). Apparently the harsh conditions imposed on organic molecules by these conditions ruptures bonds either to the silt and clay particles or within organic molecules, solubilizes significant quantities of organic matter, thereby allowing easy access by organisms to the liberated molecules.

**The Role of Organic Matter in Soil Quality**

Although organic matter is only a small percentage of the weight of most soils (usually around 1% to 6%), the amount and type of organic matter influences almost all of the properties that contribute to soil quality. The quantity and quality of soil organic matter may change a soil's properties when structure and nutrient availability improves and more biological diversity exists in soils under good organic matter management. In some cases organic matter modifies the effects of certain soil properties. The various effects of organic matter may be grouped under influences on soil physical, chemical and nutritional, and biological properties.

**Physical Effects**

The binding together of the sand, silt, and clay particles into stable aggregates helps to maintain good tilth (soil physical conditions for plant growth). Polysaccharides produced during the breakdown of organic residues plus fungal hyphae promote the development of these stable soil aggregates. A soil that is high in organic matter will have better aggregation
and tend to be less dense and allow better root penetration and development than under depleted organic matter situations. In addition, the soil will have higher infiltration rates because of a more stable surface structure that is able to resist the dispersive force of raindrop impact. The activities of larger soil organisms such as earthworms and ants also help to improve water infiltration. With more water infiltration instead of runoff, the soil will be less prone to erosion.

Sandy soils with higher levels of organic matter have more small pores to store plant available water and are less prone to drought. On the other hand, soils with more clay have better internal drainage when large amounts of organic matter are present than when depleted of organic matter.

**Chemical and Nutritional Effects**

Organic matter is a source of nutrients. Organisms decompose it and convert organic forms of elements into forms that are available for plants. In addition, organic matter is a major source of the cation exchange capacity (CEC) where it helps to "store" available nutrients and protects them from downward leaching by water. Organic molecules also chelate a number of micronutrients, such as zinc (Zn), and iron (Fe) and protect these nutrients from being converted into forms that will be less available to plants. In many soils, organic matter, because of its weak acid nature, also serves as the main source of buffering against changes in pH (Magdoff and Bartlett 1985). It can also help to protect plants from the effects of harmful chemicals, such as lowering aluminum toxicity (Hargrove and Thomas 1981).

**Other Biological Effects**

Humic materials in organic matter stimulate root and crop growth (Lee and Bartlett 1976, Chen and Aviad 1990). Although it is not clear what causes the effects, it apparently is not a direct nutritional influence.

The importance of biological diversity in soils has been stressed above. A soil high in organic matter originating from diverse sources and on which good rotations are practiced will tend to have a more diverse community of organisms and, thus, provide a more suitable biological environment for plant growth than in a soil depleted of organic matter. In general, the total biomass of soil organisms will also be higher in an organic matter-rich soil than in low organic matter soils. Because of the physical, nutritional, and chemical effects discussed above, plants in soils rich in organic matter will tend to be healthier and less susceptible to pest damage than when grown on soils partially depleted of organic matter. In addition, the presence of a diverse population of organisms when soil organic matter is plentiful helps to ensure a less hostile pest environment for crop plants. Numerous physical,
chemical, nutritional, and biological influences all combine to give organic matter an overwhelming influence on soil quality.

**Nutrient Flows and Cycling**

Not all crop nutrients in the soil are available to plants. Even if an element such as potassium is part of the structure of a grain of sand, it is not available for the plant to use. Likewise, when a nutrient such as nitrogen or phosphorus is part of the structure of a large organic molecule plants are not able to use it. Nutrients are taken up by plants from the soil solution, usually in form of simple ions such as nitrate (NO$_3^-$), phosphate ([H$_3$PO$_4^-$]), and ([HPO$_4^{2-}$]), potassium (K$^+$), magnesium (Mg$^{2+}$), and so on. Nutrients become available to plants by being solubilized or desorbed from minerals and desorbed from the cation exchange capacity of clays and well decomposed organic matter. In addition, soil organisms convert many elements from organic molecules to inorganic molecules. During this process of mineralization, the elements are changed into available forms that plants can use. Soil organic matter, thus, plays a key role in nutrient cycling, both as a source of cation exchange capacity and as a storehouse of nutrients that will be slowly converted to available forms by biological activity. As the vast majority of soil organisms participate in the decomposition process, they help to drive the recycling of nutrients.

One of the problems of conventional agricultural production is the pollution of ground and surface waters with nutrients. In addition, the relatively high quantity of available nutrients in conventional agricultural production may cause greater susceptibility to insect infestation as well as a decrease in the nutritional value of the food produced. During the year when rainfall (plus irrigation) exceed evapotranspiration, significant amounts of leaching and/or runoff can occur. If large amounts of nitrate are present at these times, substantial groundwater contamination occurs. When large quantities of commercial fertilizers or manures containing readily available nutrients are used it is possible to build up high levels of soil nitrate. This problem is widespread and regarded as a major environmental problem of national scope (Benbrook 1989, OTA 1990).

An ideal nutrient cycle would have these important characteristics. Nutrients would be present in available forms in quantities and relative proportions matched to, or synchronized with, the uptake needs of the growing crop. There would be as low a level of available nutrients as possible during the times of the year when leaching or runoff is expected. Another goal would be to decrease off-farm inputs of nutrients and, to as great an extent as possible, use nutrients from on-farm internal cycling and biological nitrogen fixation. In this "tight" nutrient cycle there would be few losses of nutrients from the farm, except as sales of crops and animals. Leaching,
volatilization, and runoff losses would be at an absolute minimum. In an ideal situation, 100% of the nutrients entering a farm as feeds, fertilizers, manures, and so forth, would leave the farm as agricultural products.

Few may ever completely reach the ideal situation described above. Leaching of nutrients in humid regions and the natural acidification processes that occur in soils cannot be completely stopped. Nor can the conversion of available nutrients into forms which are not available to plants. However, there is much room for improvement on most farms. Many of the conventional agricultural systems have extremely "leaky" nutrient cycles. Potentially "leaky" nutrient cycles can occur with many different types of agricultural activities. One example is a typical United States dairy farm. In the nutrient cycle, nutrients enter the farm as purchased feeds and minerals, purchased animals, fertilizers, and bedding (Figure 17.1). Nutrients leave the farm in the milk, animals, and crops sold, as well as in water (as runoff and leaching) and as gaseous losses. Nutrients are also cycling on the farm from soil to plant to animal to manure and back to the soil. When the difference between nutrient inputs and the nutrients in the agricultural products shipped off the farm is large, there is a large pool of excess nutrients that may cause environmental problems.

The extent of the potential problem can be gauged from an estimate of a nutrient balance of managed inputs and outputs for an 85 cow dairy farm (Table 17.2). It is interesting that a significant proportion of the N, P, and K are arriving to the farm in the form of purchased feed. It is estimated that only approximately one-third of the N, P, and K coming onto the dairy farm is leaving as milk, meat, and crops. This means that about two-thirds remains, at least temporarily. As the levels of nutrients build up in soils, the potential for polluting surface or groundwater increase dramatically.

As the ratio of animals to land area increases, and assuming that the same type of management system remains, the problem of excess nutrients coming onto livestock farm worsens dramatically. This leads to soil nutrient levels in great excess of crop needs and sets the stage for high rates of pollution in water leaching through or running over such fields.

The nutrient inputs and outputs given above are based on a conventional system that relies on confinement of dairy cows and extensive amounts of purchased feed. However, there is considerable interest in using intensively managed pasture systems to provide most of the dairy cow's forage needs during the growing season, and decreasing concentrate feeding as well (Chapter 16). If the amount of feed purchased from off the farm could be cut in half, the proportion of N, P, and K that enters the farm that are then exported, increases significantly to 54%, 48%, and 47%, respectively.
Crop and Soil Management Strategies for Promoting Soil Quality

The best way to develop a high quality soil is to manage crops and soils to promote the buildup and maintenance of high organic matter levels, including a good amount of active organic matter (Magdoff 1993). By
TABLE 17.2 Nutrient balance for an 85-cow dairy farm (after Klausner 1993).

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>feed</td>
<td>9.7</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>fertilizer</td>
<td>2.2</td>
<td>0.9</td>
<td>1.8</td>
</tr>
<tr>
<td>legume N fixation</td>
<td>1.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total inputs</td>
<td>13.0</td>
<td>2.6</td>
<td>4.2</td>
</tr>
<tr>
<td>OUTPUTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>milk</td>
<td>3.8</td>
<td>0.68</td>
<td>1.00</td>
</tr>
<tr>
<td>meat</td>
<td>0.4</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>crops</td>
<td>0.5</td>
<td>0.06</td>
<td>0.40</td>
</tr>
<tr>
<td>Total outputs</td>
<td>4.7</td>
<td>0.84</td>
<td>1.42</td>
</tr>
<tr>
<td>Outputs/Inputs (%)</td>
<td>36</td>
<td>32</td>
<td>34</td>
</tr>
</tbody>
</table>

striving to maintain that approach, the practice of good land stewardship becomes inescapable. There are many strategies available for this task and in most farm situations a number of the strategies should be used regularly.

The amount of organic matter in a particular soil is a reflection of many influences over time, both natural and of human origin. The change in organic matter content of a soil over a year's time is the difference between what has been added to the soil and what has been lost. This can be expressed by the following simple equation:

\[ \Delta \text{SOM} (\text{Soil Organic Matter}) = \text{additions} - \text{losses}. \]

When additions exceed losses, SOM builds up. Conversely, SOM decreases if losses are greater than additions. When a cropping system has been operating for a long period of time, an equilibrium is reached where the losses just equal the additions. Under these conditions there will be no change in organic matter levels.

It is clear that there are only two primary ways to build up and maintain good quantities of organic matter in soils. (1) Increase the rate of organic matter addition to soils. (2) Decrease the rate of organic matter loss.

The various techniques and strategies for organic matter management do either one or the other, and frequently do both at the same time. Although there is some overlap among the general strategies discussed below, it is worthwhile to discuss them separately.

**Better Utilization of Crop and Other Organic Residues**

In many parts of the world crop residues are viewed as a nuisance because they may harbor crop pests and sometimes interfere with soil preparation for the next crop. Thus, in-field burning of residues is not an uncommon
practice. This, however robs the soil of potentially helpful organic matter. Burning of residues reduces the energy material available to soil organisms and will result in decreased microbial biomass (Collins et al. 1992). In addition in developing countries, manures and crop residues are sometimes removed from the field to be used as fuel for cooking or heating or as building materials. These practices, while certainly more understandable than burning residues in the field, are also detrimental to the building up of soil organic matter. Not only are residues not returned in sufficient quantities, but bare soils are more susceptible to erosion, which removes topsoil enriched in organic matter. Thus better utilization of residues, for mulches as well as for incorporation into the soil, will enhance additions of organic matter to soils and slow down the amount lost by erosion.

Composting of household wastes, crop residues, as well as other locally available organic residues can provide a valuable soil amendment. Composting helps to decrease the mass of material, kill weed seeds and disease causing organisms, decrease possible noxious odors, and stabilize nutrients. Many of these materials may be available in small quantities at a time and it may not be possible or worth it to apply them directly to the soil immediately. Some materials, because of odor problems or attraction of vermin, cannot just be left unmanaged for future use. The practice of composting available organic materials thus allows the grower greater flexibility in the use of a diverse sources of residues.

Practice Good Rotations

From the point of view of soil quality, there are a number of factors to consider when evaluating rotations. By adding residues of different species of plants to soils, rotations help maintain biological diversity. This occurs because each type of plant residue, while available to many organisms, may also stimulate and/or inhibit specific soil organisms. There is a well established "rotation effect" where crops grown following almost any other crop do better than when grown in continuous monoculture. This effect is in addition to the beneficial nitrogen nutritional effects of growing a cereal crop following a legume. Some of the rotation effect may be due to the colonization of beneficial organisms around crop roots providing enhanced protection from potentially harmful organisms (Jawson et al. 1994).

Another issue to consider when evaluating rotations is the degree of soil disturbance caused by growing particular crops. Perennial crops, be they tree crops (with soil covered by cover crops or sod in between trees) or perennial forages for animals, cause significantly less soil disturbance than annual crops. The decreased disturbance, as well as the greater amounts of residues and living biomass on the soil surface given by cover crops or sod crops, will
decrease soil organic matter loss by reducing the decomposition rate and decreasing erosion of organic matter-rich surface soil.

A third issue related to rotations is that different crops will add different quantities of residues back to the soil. Perennial forage crops tend to add a lot of residues through the turnover of roots. The stem and leaf remains of many grain crops can also provide a plentiful supply of organic residues. Rotations are discussed in detail in Chapter 11.

Use Cover Crops

Since the mid-1980s there has been an increasing interest in the use cover crops. This is in fact a reawakening of interest in a practice that was used in ancient Rome some 2,000 years ago and even earlier in China. Although cover crops are discussed in detail in Chapter 10, it is important to emphasize the importance of cover crops from the point of view of soil quality. Cover crops may add organic matter to a soil when they are allowed to die or are incorporated into the soil. Cover crops, by keeping the soil covered and intercepting raindrops, decrease the breakdown of surface aggregates and thereby promote water infiltration into the soil and decrease runoff and erosion. Some cover crops, such as sweet clover, can promote the development of better soil structure by the growth of their long roots that are able to penetrate into dense subsoils.

Integrating Animals into Cropping Systems

Use of Manure

When animals are part of the cropping system it gives a number of advantages to maintaining soil quality through organic matter management. One reason is that there will be animal manures available to put onto soils. Animal manures can play a very important role in providing available nutrients for crops and to help build up soil organic matter. Another is that there will be an economic return from incorporating forage crops, such as alfalfa or clover-grass mixtures, into the rotation. These crops help to build up soil organic matter, soil structure, and add available nitrogen for succeeding crops to use. Animals can also graze off crop residues that might harbor pathogens over winter while leaving manure behind.

Reduced Tillage

In general, the greater the disturbance of the soil during soil preparation for crop growth, the greater the rate of organic matter decomposition (Reicosky and Lindstrom 1994). While this may provide some benefits in
making nutrients more rapidly available to plants, it is more difficult to maintain high levels of organic matter under conventional tillage (moldboard plow followed by harrowing), which causes major soil disturbance, than under reduced tillage systems. In addition, the use of the conventional tillage tends to promote erosion by leaving few residues to protect the surface and by decreasing natural aggregation.

The severity of soil disturbance can be greatly diminished by using reduced tillage systems for soil preparation and planting. The ultimate reduced tillage system is no-till, when only a narrow band is disturbed where the seed is to be planted. This leaves the maximum quantity of residues covering the soil. Other types of reduced tillage systems, such as chisel plowing, are also available. Reduced tillage is discussed in more detail in Chapter 11.

Erosion Control

Because eroded materials from soils are usually removed from the topsoil and are enriched in organic matter with respect to the rest of the soil, erosion is a major soil quality issue. The main problem of growing crops on eroded soils is usually that there is insufficient topsoil for best nutrition and water storage properties. Some soils are particularly prone to water and wind erosion. Soils derived from loess and containing high amounts of silt and very fine sands, such as those in the midwestern United States and north-central China's loess plateau, are sensitive to water erosion and require extra precautions. Rates of soil loss in an eroding agroecosystem in this region in China are enormous, with 100 to 200 or more tons removed per hectare per year (Hamilton and Luk 1993).

While soils high in organic matter are less prone to erosion, control of erosion also helps to maintain soil organic matter levels. Use of mulches, cover crops, sod crops, and reduced tillage (all discussed above) help to reduce the rate of soil erosion, but other specific erosion control practices may also be needed. For soils prone to erosion, tillage and planting should be done along the contour. Grassed waterways should be established to help water leave the field without cutting deep channels and land may need to be graded to help surface water flow to the waterways. Building level soil terraces for planting is another erosion control practice that can help stabilize the soil.

More Efficient Use of Nutrient Cycles

Relying on farm-based and biologically derived nutrients is a goal that should be strived toward, as well as one that is attainable on many farms. This can be done by maximizing the use of nutrients as they cycle on the
farm. Use of rotations that include sod crops with a large percentage of legume composition can provide a substantial portion of nitrogen to non-legume crops over the following two years. Reducing leaching and runoff losses of nutrients by building up soil organic matter and use of cover crops will help tighten up the nutrient cycle and promote reuse of nutrients on the field. Regular use of soil tests will also help make sure that excessive levels of available nutrients do not accumulate.
PART FIVE

Looking Ahead
Toward Sustainable Agriculture

The Problems of Modern Agriculture

Dramatic increases in crop productivity in modern agriculture have been accompanied in many instances by environmental degradation (soil erosion, pollution by pesticides, salinization), social problems (elimination of the family farm; concentration of land, resources and production; growth of agribusiness and its domination over farm production; change in rural/urban migration patterns) and by excessive use of natural resources. Recently, agriculture has become increasingly subject to the constraints of inflationary petroleum prices.

The problems of modern agriculture may become even worse when conventional western technologies, developed under specific ecological and socioeconomic conditions, are applied to developing countries, as in some Green Revolution programs (Chapter 4).

Modern farming has become highly complex, with gains in crop yield dependent on intensive management and the uninterrupted availability of supplemental energy and resources. This book is based on the premise that the modern approach is no longer appropriate in an environmentally troubled and energy-poor era; that progress toward a self-sustaining, resource-conserving, energy-efficient, economically viable and socially acceptable agriculture is warranted.

Understanding traditional farming systems may reveal important ecological clues for the development of alternative production and management systems in both industrial and developing countries.

The challenge for sustainable agriculture research will be to learn how to share innovations and insights between industrial and developing countries and to end the one-way transfer of technology from the industrial world to
the Third World. This exchange must be even, especially in the area of biotechnology, which depends greatly on the availability of crop genetic diversity, much of which is still preserved in traditional agroecosystems. It is not appropriate for plant breeders from industrial countries to have free access to native germplasm in traditional agroecosystems without compensating Third World countries.

Realistically, the search for sustainable agricultural models will have to combine elements of both traditional and modern scientific knowledge. Complementing the use of conventional varieties and inputs with traditional technologies will ensure a more affordable and sustainable agricultural production. In the United States and other industrial countries, adopting this approach will require major adjustments in the capital-intensive structure of agriculture. In developing countries it will also require structural changes, mainly to correct inequities in the distribution of resources, but it will also require that governments recognize rural people's knowledge as a major natural resource. The challenge will then be to maximize the use of this resource in autonomous agricultural development strategies.

When examining the problems that confront the development and adoption of sustainable agroecosystems, it is impossible to separate the biological problems of practicing "ecological" agriculture from the socioeconomic problems of inadequate credit, technology, education, political support and access to public service. Social complications and political biases, rather than technical ones, are likely to be the major barriers to any transition from high capital/energy production systems to labor-intensive, low energy-consuming agricultural systems.

A strategy to achieve sustained agricultural productivity will have to do more than simply modify traditional techniques. A successful strategy will be the outcome of novel approaches to designing agroecosystems that integrate management with the regional resource base and operate within the existing framework of environmental and socioeconomic conditions (Loucks 1977). Selections will have to be based on the interaction of factors such as crop species, rotations, row spacing, soil nutrients and moisture, temperature, pests, harvesting, and other agronomic procedures, and will have to accommodate the need to conserve energy and resources and protect environmental quality, public health, and equitable socioeconomic development.

These systems must contribute to rural development and social equality. For this to occur, political mechanisms must encourage substitution of labor for capital, reduce levels of mechanization and farm size, diversify farm production, and emphasize worker-controlled enterprises and/or farmers' participation in the development process. Social reforms along these lines have the added benefits of increasing employment and reducing farmers' dependence on government, credit and industry (Levins 1973).
Obviously these proposed changes may conflict with the western capitalist or neoliberal view of modern agricultural development. It may be argued, for example, that increased mechanization reduces production costs or is necessary in areas where adequate labor is unavailable, and that diversified production creates problems for mechanization. Another concern is that sustainable technologies will fail to feed as many as two billion additional people by the close of this century. Each of these criticisms may be valid if analyzed within the current socioeconomic framework. But they are less valid if we recognize that sustainable agroecosystems represent profound changes that could have major social and political implications. It is here contended that most of the present and future problems of malnourishment and starvation are due more to patterns of food distribution and low access to food because of poverty, than to agricultural limits or the type of technology used in food production.

_Biodiversity: The Key to Operationalizing Sustainable Agriculture_

As has been emphasized in this book, a key strategy in sustainable agriculture is to restore the agricultural diversity of the agricultural landscape. A critical problem in modern agriculture is the loss of biodiversity, which reaches an extreme form in agricultural monocultures. In fact, modern agriculture is shockingly dependent on a handful of varieties for its major crops. For example, in the United States, 60–70% of the total bean acreage is planted with two to three bean varieties, 72% of the potato acreage with four varieties and 53% with three cotton varieties (National Academy of Sciences 1972).

Researchers have repeatedly warned about the extreme vulnerability associated with this genetic uniformity. Nowhere are the consequences of biodiversity reduction more evident than in the realm of agricultural pest management. The instability of agroecosystems becomes manifest as the worsening of most insect pest problems is increasingly linked to the expansion of crop monocultures at the expense of the natural vegetation, thereby decreasing local habitat diversity (Altieri and Letourneau 1982, Flint and Roberts 1988). Plant communities that are modified to meet the special needs of humans become subject to heavy pest damage and generally the more intensely such communities are modified, the more abundant and serious the pest.

Therefore, one of the most important reasons for maintaining, restoring and/or enhancing biodiversity in agroecosystems is that it performs a variety of ecological services. Examples include recycling of nutrients, control of local microclimate, regulation of local hydrological processes, regulation of the abundance of undesirable organisms, and detoxification of noxious chemicals. These renewal processes and ecosystem services are largely biological, therefore
their persistence depends upon maintenance of biological diversity (Figure 18.1). When these natural services are lost due to biological simplification, the economic and environmental costs can be quite significant. Economically, in agriculture the burdens include the need to supply crops with costly external inputs, since agroecosystems deprived of basic regulating functional components lack the capacity to sponsor their own soil fertility and pest regulation. Often the costs involve a reduction in the quality of life due to decreased soil, water, and food quality when pesticide and/or nitrate contamination occurs.

In modern agroecosystems, the experimental evidence suggests that biodiversity can be used for improved pest management (Andow 1991). Several studies have shown that it is possible to stabilize the insect communities of agroecosystems by constructing vegetational architectures that support populations of natural enemies or have direct deterrent effects on pest herbivores.

In developing countries, biodiversity can be used to help the great mass of resource-poor farmers, mostly confined to marginal soils, hillsides, and rainfed areas, to achieve year-round food self-sufficiency, reduce their reliance on scarce and expensive agricultural chemical inputs, and develop production systems that rebuild the productive capacities of their small holdings (Altieri 1987). Technically, the approach consists of devising multiple-use farming systems emphasizing soil and crop protection, and achieving crop soil fertility improvement and crop protection through the integration of trees, animals, and crops. As seen in Figure 18.2, different options to diversify cropping systems are available depending on whether the current monoculture systems to be modified are based on annual or perennial crops. Diversification can also take place outside of the farm, for example, in crop-field boundaries with windbreaks, shelterbelts, and living fences, which can improve habitat for wildlife and beneficial insects, provide sources of wood, organic matter, resources for pollinating bees, and in addition, modify wind speed and microclimate (Altieri and Letourneau 1982).

Examples of grassroots rural development programs in Latin America suggest that the maintenance and/or enhancement of biodiversity in traditional agroecosystems represents a strategy that ensures diverse diets and income sources, stable production, minimum risk, intensive production with limited resources, and maximum returns under low levels of technology within these systems. The complementarity of agricultural enterprises reduces the need for outside input. The correct spatial and temporal assemblage of crops, trees, animals, soil and so on, enhances interactions and synergisms that sponsor yields and resource conservation.
The Objectives and Requirements of Sustainable Agriculture

The central issue in sustainable agriculture is not achieving maximum yield, it is long-term stabilization. The development of self-sufficient, diversified, economically viable, small-scale agroecosystems comes from novel designs of cropping and/or livestock systems managed with technologies adapted to the local environment that are within the farmers' resources. Energy and resource conservation, environmental quality, public health, and equitable socioeconomic development should be considered in making decisions on crop species, rotations, row spacing, fertilizing, pest control, and harvesting. From a management viewpoint, the basic components of a sustainable agroecosystem include:

1. Vegetative cover as an effective soil and water conserving measure, met through the use of no-till practices, mulch farming, use of cover crops, and so on
2. Regular supply of organic matter through regular addition of organic matter (manure, compost) and promotion of soil biotic activity
3. Nutrient recycling mechanisms through the use of crop rotations, crop/livestock mixed systems, agroforestry, and intercropping systems based on legumes, and similar plants
4. Pest regulation assured through enhanced activity of biological control agents achieved through biodiversity manipulations and by introducing and/or conserving natural enemies
5. Enhanced biological pest control through diversification
6. Increased multiple use capacity of the landscape
7. Sustained crop production without use of environmentally degrading chemical inputs

The above components are organized in a strategy that highlights the conservation and management of local agricultural resources following a development methodology that emphasizes participation, traditional knowledge and adaptation to local conditions (Table 18.1).

Within the framework of a participatory agroecological approach, economic, social, and environmental goals are defined by local rural communities, and low-input technologies are implemented to harmonize economic growth, social equity, and environmental preservation (Figure 18.3). Ultimately, in addition to the development and diffusion of agroecological technologies, the promotion of sustainable agriculture requires changes in the research agendas, agrarian policies, and economic systems including fair markets and prices as well as governmental incentives (Figure 18.4).
FIGURE 18.1 The integration of resources, components, and functions for multiple-use farming systems.
FIGURE 18.2 Diversification options for annual or perennial crop based cropping systems in California.
TABLE 18.1 Basic technical elements of an agroecological strategy.

1. Conservation and Regeneration of Natural Resources
   A. Soil (erosion, fertility, and plant health)
   B. Water (harvesting, in-situ conservation, management, irrigation)
   C. Germplasm (plant and animal native species, land races, adapted germplasm)
   D. Beneficial fauna and flora (natural enemies, pollinators, multiple use vegetation)

2. Management of Productive Resources
   A. Diversification
      - temporal (rotations, sequences, etc.)
      - spatial (polycultures, agroforestry, crop/livestock mixed systems
      - genetic (multilines, etc.)
      - regional (zonification, watershed, etc.)
   B. Recycling of nutrients and organic matter
      - plant biomass (green manure, crop residues, N fixation)
      - animal biomass (manure, urine, etc.)
      - reutilization of nutrients and resources internal and external to the farm
   C. Biotic regulation (crop protection and animal health)
      - natural biological control (enhancement of natural control agents)
      - artificial biological control (importation and augmentation of natural enemies, botanical insecticides, alternative veterinary products, etc.)

3. Implementation of Technical Elements
   A. Definition of resource regeneration, conservation and management techniques tailored to local needs and agroecological-socioeconomic circumstances.
   B. The level of implementation can be at the microregion watershed level, farm level and cropping system level.
   C. The implementation is guided by a holistic (integrated) conception and therefore does not emphasize isolated elements.
   D. The strategy must be in agreement with the peasant rationale and must incorporate elements of technical resource management.

The Transition Toward Sustainable Agriculture

The structure of corporate agriculture and the organization of agricultural research (which focuses on short-term problems and incremental modifications of existing technology) prevent ecological research recommendations from being incorporated into agricultural management systems (Buttell 1980a). It is obvious that agricultural enterprises will not invest in sustainable technologies for which the profits cannot be immediately captured.
In fact, emphasis on bigger yields continues, and in the 1980s this high technology approach is epitomized by the wide-scale promotion of biotechnology, claimed as the new technological fix that can circumvent low productivity, especially in Third World agriculture (Barton and Brill 1983). It is argued that cell and tissue culture could be used immediately to accelerate the production of drought-tolerant and disease-resistant crop varieties. Embryo transplantation offers the possibility of improved livestock species. Thus, proponents contend that culturing and genetic transfer technologies can quickly provide plant materials adaptable to most areas in the world, including marginal lands.

An important dilemma for developers will be how to transfer and adapt biotechnologies to the social, economic, and political conditions prevalent in developing countries. Given the present economic situation in these countries, it is reasonable to expect that biotechnologies promoted in debt-burdened developing countries might not be those best suited to local ecological and economic environments, but rather those most attractive to the large markets of the industrial nations (Kenney and Buttel 1984, Hansen et al. 1984).

As use of this technology increases, regulations will have to emerge to protect the public from environmental and health problems that may arise from the release of genetically engineered organisms (Brill 1985). Some concern exists that testing or application could lead to "ecological release" from biotic regulation of the genetically engineered organisms themselves or other biota in the same habitat. Third World bureaucracies are often slow or inefficient at enforcing safety, a situation exploited by many transnational companies to market their products banned in the developed countries.

Although biotechnology proponents argue that the plants they produce may be resistant to many pests and able to thrive in nutrient-poor soils (thus decreasing the need for pesticides and fertilizers), the approach makes farmers, especially peasants, increasingly dependent on seed companies. Given the tendency of some companies to emphasize seed/chemical "packages," farmers would also become automatically dependent on the chemicals needed to grow the seeds (Buttel 1980b). This is particularly true in the case of biotechnologies that tailor crops to specific needs (such as herbicide-resistant crops). The problem is that when farmers lose their autonomy, their production systems become governed by distant institutions over which rural communities have little control.

On the other hand, in industrial countries consideration of mixed agriculture (polycultures) is inhibited by the present land tenure system and the design of farm machinery. Therefore, research into the ecology of polycultures only makes sense as part of a broader program that includes land reform and redesign of machines (Levins 1973). Other limitations under prevailing societal conditions make the adoption of ecological farming difficult.
FIGURE 18.3 The role of agroecology in satisfying social, environmental, and economic goals in rural areas.
FIGURE 18.4 The requirements for a sustainable agriculture.
• Given the environmental complexity of each farming system, sustainable agricultural technologies must be site-specific. Therefore, technologies developed at experiment stations may prove inadequate in a heterogeneous region of sustainable agroecosystems.

• A holistic exploration of agroecosystem design, management, and structure would tend to break down disciplinary boundaries, challenging the commodity-oriented bias of current agricultural education, research, and extension, and also the inflexible structure of the urban/rural markets.

• During a transitional phase, crop yields and cosmetic quality would vary to some degree, resulting in unpredictable production, which in turn inhibits capital investment and prevents farmers from establishing stable and profitable relationships with wholesalers and processors. Many farmers will not shift to alternative systems unless there is a good prospect for monetary gain brought about by either increased output or decreased production costs. Different attitudes will depend primarily on farmers’ perceptions of the short-term and long-term economic benefits of sustainable agriculture.

Apparently, it will not be possible to overcome these limitations without major changes in the structure of United States agriculture. The process of change could be accelerated if:

1. Agricultural research and extension focused attention on long-term problems, emphasizing small-scale, site-specific technologies developed in farmers’ fields, with the active cooperation of small farmers.

2. Agricultural planning was integrated with an ecological perspective for all land use, pursuing multiple goals, such as production of food and income, improvement of nutritional quality, protection of the health of farm workers and consumers, protection of the environment, and equitable partitioning of the population between urban and rural settlement (Levins and Lewontin 1985).

3. Producer-consumer cooperatives emerged, encouraging local markets, and farmer cooperatives coordinated production goals to prevent over or under production, and to establish "objective" cosmetic standards.

4. Farming became a family-oriented activity, based on cooperative decisions about items such as farm management, purchase of inputs, credit and labor assignments.

5. Small farmers organized and became a strong political constituency to ensure just land reforms, appropriate legislation, and improved access to public services, credit, and technology.
6. Agriculture became subject to society-wide public policy decisions that subordinate agricultural resource management interests to broader political and economic interests.

7. Consumers became more effective in challenging agricultural research agendas that ignore nutrition, health, and environmental issues.

The requirements to develop a sustainable agriculture clearly are not just biological or technical, but also social, economic, and political, and illustrate the requirements needed to create a sustainable society. It is inconceivable to promote ecological change in the agricultural sector without advocating comparable changes in all other interrelated areas of society. The final requirement of an ecological agriculture is an evolved, conscious human being whose attitude toward nature is that of coexistence, not exploitation.
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About the Book and Author

This new edition builds on the explosion of research on sustainable agriculture since the late 1980s. By separating myth from reality, Miguel Altieri extracts the key principles of sustainable agriculture and expounds on management systems that “really work.” Providing case studies of sustainable rural development in developing countries, he goes beyond a mere description of practices to include data that reveal the socioeconomic and environmental impacts of alternative projects.

Each chapter of Agroecology has been enriched and updated with the latest research results from around the world. New emphasis has been placed on such issues as the ecological economics of agriculture, policy changes needed for promoting sustainable agriculture, rural development in the Third World, the role of biodiversity in agriculture, and new research methodologies.

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