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The Ecological Role and Enhancement Of Biodiversity in Agriculture

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Biodiversity in agriculture, or agrobiodiversity, refers to all crops and animal breeds, their wild relatives, and other species (e.g. pollinators, symbionts, pests, parasites, predators, decomposers, and competitors) that co-exist and interact within crop lands and/or their surrounding environments (Altieri, 1999). It includes populations of variable and adaptable landraces, as well as wild and weedy relatives, from which the entire range of domestic crops is derived (Harlan, 1975). Components of agrobiodiversity include genes, populations, species, communities, and ecosystems, as well as the landscapes in which agroecosystems are embedded.

Most components of agrobiodiversity perform ecological functions and deliver services that sustain ecosystem processes and the natural resource base upon which agriculture depends. Ecosystem services beyond the production of food, fibre, fuel, and income include the recycling of nutrients, control of microclimates, regulation of hydrological processes, pollination, regulation of undesirable organisms, and detoxification of noxious chemicals. All renewal processes and ecosystem services performed by agrobiodiversity are largely biological. Therefore, their persistence depends upon the maintenance of biological diversity (Altieri and Nicholls, 2004a). When these natural services are lost due to biological simplification, the economic and environmental costs can be significant. For example when agroecosystems, deprived of their basic functional components, lack the capacity to sponsor their own soil fertility and pest regulation, external inputs are needed to supply crops with these services. This can have negative economic consequences and create a suite of environmental problems.

Biodiversity simplification in agriculture results in an artificial ecosystem that requires constant human intervention. While, in natural ecosystems, the internal regulation of function is a product of plant biodiversity through flows of energy and nutrients, under agricultural intensification this form of control is progressively lost (Swift and Anderson, 1993). Thus commercial seedbed 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 (Cox and Atkins, 1974).

A growing number of scientists, farmers, and private citizens fear for the long-term sustainability of ecologically simplified and highly input-dependent food production systems. Questions are being raised about the loss of biodiversity, the loss of productive capacity through soil erosion, the growing dependence of modern agriculture on non-renewable resources, the heavy reliance on chemical fertilizers and pesticides, and the vulnerability of large-scale monocultures to climate change and pest-disease outbreaks.

These concerns have gained renewed attention with the expansion of transgenic crops and agrofuel plantations which, by 2007, covered 115 million hectares worldwide—mostly with monocultures of soybean and maize (Altieri, 2007). The expansion of these technologies into developing countries may not be wise or desirable, especially if the promotion of these monocultures results in serious social and environmental problems. These countries are rich in agricultural diversity; traditional and small farmers have historically used mixed farming systems with high degrees of plant diversity, in the form of polycultures, agroforestry, and animal integration patterns, providing a strong ecological foundation to sustain small farm productivity and to design agroecological models that benefit the rural poor under varying climatic conditions and marginal environments (Altieri, 1995). Furthermore, large numbers of farmers in developing countries have limited access to the synthetic inputs that substitute for ecological services in intensified agricultural systems and may particularly benefit from the maintenance and enhancement of biodiversity (Francis, 1986).

Worldwide, experimental evidence suggests that biodiversity can be used to enhance soil fertility and improve pest management while sustaining acceptable yields without dependence on external inputs (Altieri and Letourneau, 1984; Andow, 1991). For example, several studies have shown that it is possible to stabilize insect communities in agroecosystems by promoting vegetational infrastructures that support natural enemy populations (Landis et al, 2000; Schellhorn et al, 2008; Lundgren et al, 2009) and to enhance soil biota—which play important roles in organic matter decomposition, nutrient cycling and soil-borne disease suppression—through the use of antagonists (Magdoff and van Es, 2000).

After exploring the key roles and functions of biodiversity in agroecosystem function, this chapter analyses the various options of agroecosystem design which, based on current agroecological theory, should provide for the optimal use and enhancement of functional biodiversity in crop fields.

Modern agriculture and biodiversity

Modern agriculture has led to the simplification of environmental structure over vast areas, replacing nature's diversity with a small number of cultivated plants and domesticated animals. In fact, the majority of the world's agricultural landscapes are planted with some 12 species of grain crops, 23 vegetable crop species, and about 35 fruit and nut crop species (Fowler and Mooney, 1990); that is, no more than 70 plant species spread over approximately 1,440 million hectares of presently cultivated land. Added to this problem is the genetic homogeneity that exists within some of the most commonly planted crops. For example, in the United States, 60 to 70 percent of the total bean acreage is planted with two to three bean varieties, 72 percent of the potato acreage with four varieties, and 53 percent of the cotton acreage with three varieties (NAS, 1972) Researchers have repeatedly warned about the extreme vulnerability associated with this genetic uniformity (Tripp, 1996; Brush et al, 2003; Gepts, 2006).

Cultivated plants grown in genetically homogeneous monocultures often do not possess the necessary ecological defence mechanisms to tolerate outbreaks of pests or disease. Modern agriculturalists have selected crops for high yields and high profitability, sacrificing natural resistance to pests and disease for productivity (Robinson, 1996). While significant amounts of toxic secondary compounds remain in many edible crops, the general trend has been the gradual reduction of the chemical and morphological (physical) features that protect plants. This is coupled with the simplification of the production environment inherent in monoculture agriculture. Not only are fewer species present in monocultures—reducing adaptive capacity—ecological niches are left unoccupied and open to colonization by pest species. As a result, crop plants are usually more vulnerable than their wild relatives to pest and disease attack and agroecosystems are subject to more frequent insect outbreaks than are natural ecosystems, despite intensive human inputs (Altieri and Nicholls, 2007).

Modern agricultural practices such as pesticide application also negatively affect natural enemies (predators and parasites) and key soil biota components, which do not thrive well in toxic environments. Further, a new wave of environmental effects may be associated with the massive deployment of transgenic crops whose effects are not limited to pest resistance and the creation of new weeds or virus strains (Marvier, 2001). Transgenic crops can produce environmental toxins with potential to move through the food chain and precipitate a series of unintended consequences for key ecological processes. These toxins may negatively affect biocontrol agents such as invertebrate populations which, in turn, can affect nutrient cycling. These toxins can also persist in the soil profile by binding to colloids. It is not yet possible to determine the specific long-term impacts of transgenic crops on agrobiodiversity and the ecological processes it mediates (Altieri, 2007). However, as long as monocultures remain the structural foundation of modern agricultural systems, agroecological research suggests that pest problems will persist (Altieri and Nicholls, 2007; Figure 2.1).

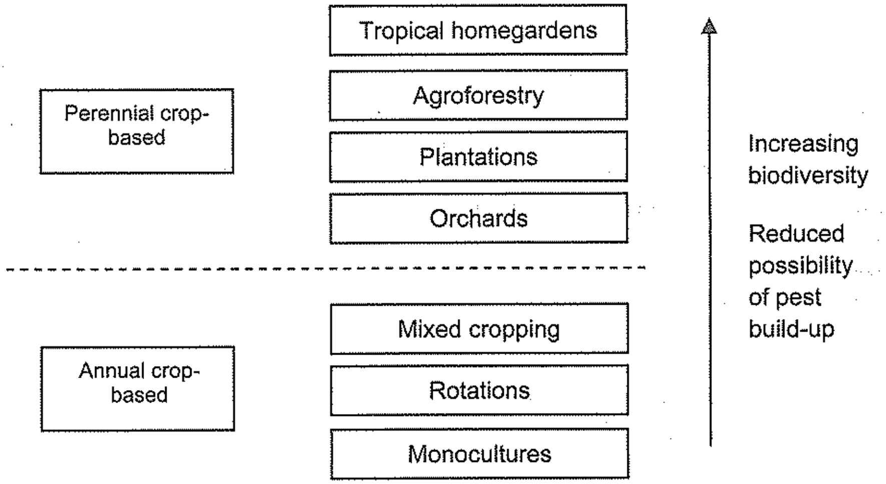

Figure 2.1. A classification of dominant agricultural agroecosystems on a gradient of diversity and vulnerability to pest outbreak.

One of the major challenges for those advocating ecological forms of agricultural production is to develop strategies to overcome the ecological limits imposed by biodiversity-poor monocultures. The promotion of biodiversity within agricultural systems is the cornerstone strategy for overcoming such limits. Associated with this is the redesign of agroecosystems at multiple scales with a view to improving the diversity of associated biota, which in turn generally leads to more effective pest control, pollination and tighter nutrient cycling (Altieri, 1995; Gliessman, 1998). As more information about the specific relationships between biodiversity, ecosystem processes, and productivity in a variety of agricultural systems is accumulated, guidelines for design can be developed further and used to improve agroecosystem sustainability and resource conservation.

Biodiversity in traditional farming systems

A conspicuous feature of traditional farming systems is the degree of plant diversity in the form of polycultures and/or agroforestry patterns (Altieri, 2000). Traditional cropping systems are also genetically diverse, containing numerous varieties of domesticated crop species as well as their wild relatives. Maintaining genetic diversity appears to be of even greater importance as land becomes more marginal and hence farming more risky. For example in Peru, where farmers plant up to 50 varieties of potato, the number of potato varieties cultivated increases with the altitude of the land farmed. Genetic diversity confers at least partial resistance to diseases that are specific to particular strains of crops and allows farmers to exploit different soil types and microclimates for a variety of nutritional and other uses (Brush, 1982).

These diversified agroecosystems have emerged over centuries of cultural and biological co-evolution and represent the accumulated experiences of peasants interacting with the environment with limited access to external inputs, capital, or scientific knowledge (Wilken, 1987). Using inventive self-reliance, experiential knowledge, and locally available resources, peasants have often developed farming systems adapted to local conditions that generate sustained yields and meet subsistence needs, despite marginal land endowments and the low use of external inputs (Altieri, 2002). Interactions between crops, animals and trees result in beneficial synergisms that allow biodiverse agroecosystems to sponsor their own soil fertility, pest control and productivity (Marten, 1986; Wilken, 1987; Altieri, 1995; Vandermeer et al, 1998), such as:

- Interplanting crops that enrich the soil with organic matter counteracts the tendency of certain crops to deplete the soil;
- Intercropping diverse plant species provides habitat for the natural enemies of insect pests as well as alternative host plants for pests;
- Mixing different crop species or varieties can delay the onset of diseases, reduce the spread of disease-carrying spores and modify environmental conditions such as humidity, light, temperature and air movement, so that they are less favourable to the spread of certain diseases; and
- Many intercropping systems prevent competition from weeds by creating complex canopies that block sunlight from reaching sensitive weed species, or by allelopathic inhibition of germination and growth of weeds.

The sustainability of intercropping, agroforestry, shifting cultivation and other traditional farming methods derives, in part, from their mimicry of natural ecological processes. This use of natural analogies suggests principles for the design of agricultural systems that make effective use of sunlight, soil nutrients, rainfall, and biological resources (Ewell, 1986). Much of the anthropological and ecological research conducted on traditional agriculture has shown that when not disrupted by economic or political forces, most indigenous modes of production have a strong ecological basis and lead to the regeneration and preservation of biodiversity and natural resources. Several scientists now recognize that traditional farming systems can be models of efficiency as these systems incorporate careful management of soil, water, nutrients, and biological resources. By studying these systems, ecologists can enhance their understanding of the dynamics of complex systems, especially the relationship between biodiversity and ecosystem functioning, thus enriching ecological theory. Moreover, principles can be derived for practical application in the design of more sustainable farming systems appropriate to small farmers in the developing world. In fact, several advances in modern agroecology have resulted from the study of traditional agroecosystems and a series of novel agroecosystem designs have been modelled after successful traditional farming systems (Altieri, 2004).

Organic agriculture and biodiversity

Most practitioners and supporters of organic agriculture believe that organic farms have positive impacts on biodiversity, and that farmland under organic agriculture does not exhibit the same dramatic decline in biodiversity that occurs in conventional agricultural farmland. These biodiversity benefits are likely to derive from the specific environmental features and management practices employed within organic systems, which are either absent or rarely utilized in the majority of conventional systems (Lampkin, 1992). The use of biological and management practices by organic farmers to manage fertility and pests, such as green manuring, composting, intercropping, and rotation, encourage habitat heterogeneity and floral diversity. These are known to benefit invertebrate and vertebrate biodiversity across a range of taxa.

Clearly, the benefits to biodiversity of organic farming may vary according to factors such as location, climate, crop-type and species, and are likely to be strongly influenced by the specific management practices adopted. One European study, for example, found 9 to 11 weed species in organically managed wheat plots compared with one species in conventional plots (Mader et al, 2002). It also found between 28 and 34 carabid species in organic systems as opposed to 22 to 26 species in conventional systems. Some specialized and endangered species were present only in the organic systems. This difference can largely be explained by the effects of pesticides. A particularly remarkable finding was a significant increase in soil microbial diversity in the organic systems, which in turn mediated soil fertility in low-input fields.

One of the most complete analyses of the effects of organic agriculture on biodiversity, which included the review of 76 published studies, found that species abundance and/or richness, across a wide range of taxa, was higher on organic farms than on locally representative conventional farms (Hole et al, 2005). The majority of these studies recorded higher weed abundance and species richness in fields under organic management, regardless of the arable crop being grown. Although differences in microbial (bacteria and fungi) communities between organic and conventional systems were less dramatic, there was evidence of a general trend towards elevated bacterial and fungal biomass and activity under organic systems. Comparative studies also indicated a general trend for higher earthworm abundance and species diversity in the organic systems.

The review by Hole et al (2005) indicates that the biodiversity benefits of organic management are likely to accrue through the provision of a greater quantity and quality of both crop and non-crop habitat than on conventional farms. Three broad organic management options seem to be particularly beneficial to farmland biodiversity: (1) prohibition/reduced use of chemical pesticides and synthetic fertilizers; (2) sympathetic management of non-crop habitats and field margins; and (3) preservation of mixed farming. While these three biodiversity friendly management options are characteristic of most organic farming operations they are certainly not ubiquitous or unique. Some organic farms are highly specialized, large-scale and monocultural operations managed with the same input-substitution pproach that characterizes conventional agriculture, merely replacing the use of isallowed synthetic inputs with bacteriological herbicides, sulphur-based ungicides and naturally-derived fertilizers (Lockie et al, 2006). Such farms usually ontain low levels of plant, arthropod and microbial biodiversity despite their ompliance with organic certification standards (Altieri, 2002). At the same time, a ariety of approaches to agricultural sustainability that are not specifically organic ncorporate, to varying degrees, the three key practices mentioned above. These nclude Integrated Pest Management, Whole Farm Planning, Fair Trade etc (Lockie t al, 2006).

Managing planned and associated biodiversity

Two distinct components of biodiversity can be recognized in agroecosystems. The first, planned biodiversity, includes the crops and livestock purposely included in an agroecosystem. The second component, associated biodiversity, includes all the soil flora and fauna, herbivores, carnivores, decomposers etc that colonize the agroecosystem from surrounding environments. The functional relationship between these components and the ecosystems of which they are a part is illustrated in Figure 2.2. Both planned and associated biodiversity have direct functions in the provision of ecosystem services as illustrated by the bold arrows. However, planned biodiversity also has an indirect function, illustrated by the dotted arrow in the figure, which is realized through its influence on associated biodiversity (Vandermeer and Perfecto, 1995).

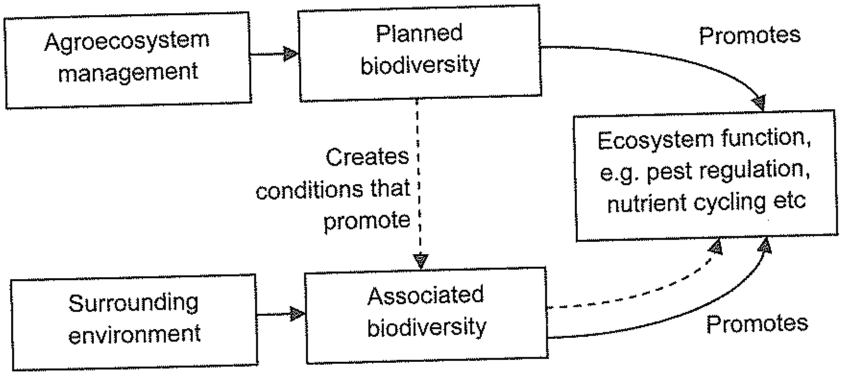

Figure 2.2. The relationship between planned and associated biodiversity in promotion of ecosystem function (adapted from Vandermeer and Perfecto, 1995).

Complementary interactions between the various biotic components of agroecosystems can be of a multiple nature. Some of these interactions can be used to induce positive and direct synergisms and effects on the biological control of specific crop pests and plant diseases, soil fertility regeneration and soil conservation. The exploitation of these interactions in real situations involves agroecosystem design and management and requires an understanding of the numerous relationships between soils, microorganisms, plants, insect herbivores, and natural enemies (Altieri and Nicholls, 2004b). According to agroecological theory, the optimal behaviour of agroecosystems depends on the level of interaction between the various biotic and abiotic components. By assembling a functional biodiversity it is possible to initiate synergisms which subsidize agroecosystem processes by providing ecological services such as the activation of soil biology, the recycling of nutrients, the enhancement of beneficial arthropods and antagonists, and so on (Altieri, 1995; Gliessman, 1998).

Agroecology aims to exploit the complementarity and synergisms that result from combining different components of both planned and associated biodiversity including crops, trees, and animals in spatial and temporal arrangements such as polycultures, agroforestry systems, and crop-livestock mixtures. Agroecologists encourage agricultural practices which increase the abundance and diversity of above and below-ground organisms and which in turn provide key ecological services to agroecosystems (Reijntjes et al, 1992).

Agroecosystem biodiversity components and their ecological function

Beneficial insects: predators and parasitoids

Increasing the richness of a particular guild of predators or parasitoids, or both, can reduce the density of a widespread group of herbivorous pests and, in turn, increase the yield of economically important crops. Experience with biological control suggests that when enemy species act together, the population density of specific pests is suppressed more than could be predicted from the summed impact of each enemy species alone (Debach and Rosen, 1991). Experience also suggests that this is more likely to occur in polycultural than in monocultural agroecosystems (Andow, 1991). Although most research has documented insect population trends in single versus complex crop habitats, a few have concentrated on elucidating the nature and dynamics of the relationships between plants and herbivores—and between herbivores and their natural enemies—in diversified agroecosystems. Several lines of research have developed (Altieri and Letourneau, 1982, 1984; Altieri, 1994, 1995):

- 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) harbour beneficial arthropods that suppress pest populations.
- Insect dynamics in annual polycultures: overwhelming evidence suggests that polycultures support a lower herbivore load than do monocultures. Relatively more stable natural enemy populations persist in polycultures due to the more continuous availability of food sources and micro-habitats, while specialized

herbivores are more likely to find and remain on pure crop stands that provide concentrated resources and monotonous physical conditions.

- Herbivores in complex perennial crop systems: orchards with rich floral undergrowth exhibit a lower incidence of insect pests than clean cultivated orchards due to the increased abundance and efficiency of predators and parasitoids. In some cases, ground cover directly affects herbivore species, which discriminate between trees with and without cover beneath.
- Pest management in agroforestry systems: like other polycultures, insect populations are more stable in complex agroforestry systems because a diverse and more permanent habitat can maintain an adequate population of the pest and its enemies at critical times (van den Bosch and Telford, 1964).
- The effects of adjacent vegetation: one way to re-introduce biodiversity into large-scale monocultures is by establishing diverse vegetation along field margins and/or hedgerows which may serve as biological corridors allowing the movement and distribution of useful arthropod biodiversity within agroecosystems (Boaltman, 1994).

The available literature suggests that the design of vegetation management strategies must include knowledge and consideration of: (1) crop arrangement in time and space; (2) the composition and abundance of non-crop vegetation within and around fields; (3) the soil type; (4) the surrounding environment; and (5) the type and intensity of management. The response of insect populations to environmental manipulations depends upon their degree of association with one or more of the vegetational components of the system. Extension of the cropping period or planning temporal or spatial cropping sequences may allow naturally occurring biological control agents to sustain higher population levels on alternate hosts or prey and to persist in the agricultural environment throughout the year.

Since farming systems in a region are managed over a range of energy inputs, levels of crop diversity, and successional stages, variations in insect dynamics are likely to occur and may be difficult to predict. Planning of a vegetation management strategy in agroecosystems must therefore take into account local variations in climate, geography, crops, local vegetation, inputs, pest complexes etc, which might increase or decrease the potential for pest development under some vegetation management conditions. The selection of component plant species can also be critical. Systematic studies on the quality of plant diversification with respect to the abundance and efficiency of natural enemies are needed. As pointed out by Southwood and Way (1970), what seems to matter is functional diversity and not diversity per se. These effects of diversification can only be determined experimentally across a wide range of agroecosystems. The task is formidable since enhancement techniques must necessarily be site specific.

Beneficial insects: pollinators

Pollination is critical to the overall maintenance of biodiversity, as over 200,000 flowering plant species depend on pollination. In agroecosystems, pollinators are ssential for orchard, horticultural and forage production, as well as the production f seed for many root and fibre crops. Data from 200 countries revealed that fruit, egetable or seed production from 87 of the leading global food crops is dependent pon animal pollination (Klein et al, 2007).

As farm fields have become larger, and the use of agricultural chemicals has ncreased, mounting evidence points to a potentially serious decline in populations f pollinators. In agroecosystems, pollinator diversity and abundance is critically dependent on the availability of natural habitat in proximity to the farm site. Farm management may also influence the diversity and abundance of native bees found on farms (Kremen et al, 2008). On organic farms near natural habitat, native bee communities were found to be capable of providing full pollination services even for crops with heavy pollination requirements (e.g. watermelon, *Citrullus lanatus*), without the intervention of managed honeybees. Conventional farms experienced greatly reduced diversity and abundance of native bees, resulting in insufficient pollination services from native bees alone.

Agricultural intensification simultaneously reduces the richness, abundance and biomass of bees, and promotes local extinction of the most efficient bee pollinators. Pollinator populations have been adversely affected by increased pesticide use and much of their natural habitats, which includes hedgerows, dead trees and old fence posts, have been destroyed to make room for more farmland. There is ample evidence to suggest that pollinator populations are in decline and that such declines are affecting agricultural productivity (Ricketts et al, 2008). A global shortage of bees and other insect pollinators is reducing crop yields around the world and could lead to far higher prices for fruits and vegetables (Kevan et al, 1990).

The ecological role of weeds

Although weeds may compete with crop species, research shows that weeds play an important role in supporting biodiversity within agroecosystems. Several studies have demonstrated that the presence of weeds within or around crop fields influences the dynamics of the crop and associated biotic communities (Fiedler et al, 2008; Hyvonen and Huusela-Veistola, 2008). The manipulation of a specific weed species, a particular weed control practice, or the level of weediness of a cropping system can affect the ecology of insect pests and associated natural enemies (Altieri and Letourneau, 1982).

Weeds also positively affect the biology and dynamics of beneficial insects, and offer many important requisites for natural enemies such as alternative prey/hosts, pollen, or nectar as well as microhabitats that are not available in weed-free monocultures (Altieri and Letourneau, 1984). As insect pests are not always present in annual crops the provision of resources such as alternate host locations and pollen-nectar can contribute to the persistence of viable natural enemy populations in the absence of pests.

Research has shown that outbreaks of certain types of crop pests are less likely to occur in weed-diversified crop systems than in weed-free fields, mainly due to the increased mortality imposed by natural enemies. Crop fields with a dense weed cover and high diversity usually have more predacious arthropods than weed-free fields. The successful establishment of parasitoid populations usually depends on the presence of weeds that provide nectar for adult female wasps. Examples of cropping systems in which the presence of specific weeds has enhanced the biological control of particular pests have been reviewed by Altieri and Nicholls (2004). A literature survey by Baliddawa (1985) showed that population densities of 27 insect pest species were reduced in weedy crops compared to weed-free crops.

Research also suggests that interactions of weeds with arbuscular-mycorrhizal fungi (AMF) can increase the beneficial effects of weeds on the functioning of agroecosystems. Through a variety of mechanisms, weed-AMF interactions may reduce crop yield losses to weeds, limit weed species shifts, and increase positive effects of weeds on soil quality and beneficial organisms (Jordan et al, 2000).

Soil biota

Soil provides habitat for a diverse array of organisms—microbes (fungi, bacteria and actinomycetes) and animals such as nematodes, mites, collembola, diplopoda, earthworms and arthropods (Davies, 1973), which contribute to the maintenance and productivity of agroecosystems. The rhizosphere, which is the interface between plant roots and the soil environment, is the location of much soil biological activity and plant-microbe interactions including symbioses, pathogenic infection, and competition. A square metre of an organic temperate agricultural soil may contain 1000 species of organisms with population densities in the order of 106 per square metre for nematodes, 105 per square metre for micro arthropods, and 104 per square metre for other invertebrate groups. One gram of soil may contain over a thousand fungal hyphae and up to a million or more individual bacterial colonies. Energy, carbon, nitrogen and other nutrient fluxes through the soil's decomposing subsystem are dominated by fungi and bacteria, although invertebrates play a certain role in nitrogen flux (Swift and Anderson, 1993). The types of species present and their level of activity depends on micro-environmental conditions including temperature, moisture, aeration, pH, pore size, and types of food sources.

The community of soil organisms incorporates plant and animal residues and wastes into the soil and digests them, creating soil humus, which is a vital constituent for good physical and chemical soil conditions, and the recycling of carbon and mineral nutrients. This decomposition process includes the release of carbon dioxide to the atmosphere where it can be recycled through higher plants, and the release of essential plant nutrients in inorganic forms that can be absorbed by plants. Also, since the microbial biomass itself is a relatively labile fraction of the soil organic matter, nutrients in the biomass become available as live microbes digest dead microbial cells.

There is evidence that soil microbial diversity confers protection against soil-borne disease, but crop and soil type and management also play a role. Studies show that mycorrhizal diversity positively contributes to nutrient and, possibly, water use efficiency. The effects of soil fauna on nutrient and water use efficiencies are also apparent, but diversity effects may be indirect, through effects on soil structure (Giller et al, 1997).

There is no doubt that soil organisms are fundamentally important to the functioning of agroecosystems. Various functional groups of soil biota have been proposed such as: roots, ecosystem engineers, litter transformers, phytophages and parasites, micro-predators and microflora. In their role as regulators of soil ecosystem processes, soil organisms perform a number of vital functions in support of soil physical structure and chemical fertility including:

- Decomposition of plant residues, manures, and organic wastes;
- Humus synthesis;
- Improvement of soil structure;
- Mineralization of organic N, S, and P;
- Increase in the availability of plant nutrients; for example, P, Mn, Fe, Zn, Cu;
- Biological nitrogen fixation;
- Plant growth promotion: growth hormones, changes in seed germination, floral development, root and shoot biomass;
- Altering soil structure and aggregation;
- Suppressing pathogenic organisms;
- Breakdown of toxic compounds;
- Biological control of weeds for example, biological herbicides; and
- Enhanced drought tolerance of plants (Hendrix et al, 1990; see also Magdoff and van Es, 2000).

Given the ecological services provided by soil biodiversity, soil organisms are crucial for the sustainability of agroecosystems. Therefore, it is important to define and encourage agricultural practices that increase the abundance and diversity of soil organisms by enhancing habitat conditions, soil organic matter content and resource availability, and to avoid practices that reduce soil biodiversity. Sustained agricultural productivity may depend on the selection of management practices that enhance soil biological function in the fixation of atmospheric nitrogen, recycling of carbon and nutrients, and suppression of soil pathogens.

The types of agricultural management practices that influence soil biological activity are those that enhance nutrient cycling, add carbon and nitrogen inputs, improve the soil physical environment, and avoid synthetic chemicals that can harm soil microbial and faunal activity. Such practices include the use of cover crops and/or green manures, inclusion of a high-residue crop or perennial sod, applications of manure or compost, and reduced tillage and lower use of nitrogen fertilizers.

Reduced tillage (with surface placement of residues) creates a relatively more stable environment and encourages development of more diverse decomposer communities and slower nutrient turnover. Evidence suggests that conditions in no-till systems favour a higher ratio of fungi to bacteria, whereas in conventionally tilled systems bacterial decomposers may predominate (Hendrix et al, 1990). Residue has an important effect on organic substrate availability and soil micro-climatic characteristics. Soils with residues chopped and left as mulch generally support higher populations of surface feeding earthworms. Soil unprotected by surface mulch will freeze much faster than mulched soil and earthworm mortality increases in the absence of a gradual period of adjustment to decreasing temperatures (Davies, 1973).

Soil biotic populations can also be increased through direct introduction of organisms. Earthworms have been commonly introduced in a number of instances for soil conditioning and enhanced soil structure and fertility. Inoculation of seeds or roots with rhizobia, mycorrhizae, and Trichoderma are examples of direct manipulations of microflora to enhance plant performance (Miller, 1990). A major problem to overcome in the use of inoculations and introductions is ensuring the establishment of the introduced organisms. Competition from a diverse indigenous soil biota may overwhelm introduced organisms. Additionally, limited availability of food resources may result in extinction or emigration. It may be necessary to add food supplies or organic amendments along with inocula to aid establishment (Miller, 1990).

Most agricultural plants are colonized by mycorrhizal fungi, which have a substantial impact on crop productivity. Many studies have demonstrated the dramatic plant growth response achieved following inoculation with mycorrhizal fungi in low-fertility soils. These organisms can be used as bio-fertilizers but responses are often disappointing, especially in high-input agricultural systems. Management practices such as pesticides, tillage, crop rotation, and fallowing may adversely affect populations of mycorrhizal fungi in the field.

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 (Fry, 1982).

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.

Conclusion

This chapter presents some ideas and principles on how to design and manage biodiverse farms that are rich in beneficial insect fauna and soil biota. Diversity—both agricultural and biological—becomes one of the integral foundations of such farming systems. Polycultures are typically favoured over monocultures and perennial, reduced-till systems with high species diversity are emphasized to reduce negative impacts resulting from intensive annual cropping systems. Rather than subsidizing soils, overdrafting groundwater, or relying on high-input fertilizers and pest control chemicals, practitioners work with planned and associated biodiversity and their synergisms to boost biological efficiency. Wild habitats may be incorporated to establish populations of beneficial insects and pollinators. Cover cropping and/or animals provide on-site sources of organic matter and nutrients.

Locally adapted varieties and species can create regionally specific genetic resilience. In this approach, the use of local biodiversity should be prioritized.

Clearly, a key strategy in sustainable agriculture is to reincorporate diversity into the agricultural landscape through various cropping designs. Emergent ecological properties develop in diversified farms, which allow the system to function in ways that maintain soil fertility, crop production, and pest regulation. The main approach is to use management methods that increase agroecosystem diversity and complexity (in space and time) as a foundation for establishing beneficial interactions that keep pest populations in check and maintain soil quality.

Different options to diversify cropping systems are available depending on whether the current monoculture systems that will be modified are based on annual or perennial crops. Diversification can also take place outside the farm. For example, field boundaries can be diversified with windbreaks, shelterbelts, and living fences to improve habitat for wildlife and beneficial insects. Additional benefits of these strategies include providing resources of wood, organic matter, resources for pollinating bees, and, in addition, modify wind speed and microclimate. Plant diversification can be considered a form of conservation biological control with the goal of creating a suitable ecological infrastructure within the agricultural landscape to provide resources such as pollen and nectar for adult natural enemies, alternative prey or hosts, and shelter from adverse conditions. These resources must be integrated into the landscape in a way that is spatially and temporally favourable to natural enemies and practical for producers to implement.

In summary, key ecological principles for the design of diversified and sustainable agroecosystems include:

- Increasing species diversity as this promotes fuller use of resources (nutrients, radiation, water etc), pest protection and compensatory growth. Many researchers have highlighted the importance of various spatial and temporal plant combinations to facilitate complementary resource use or to provide intercrop advantage such as in the case of legumes facilitating the growth of cereals by supplying extra nitrogen. Compensatory growth is another desirable trait as if one species succumbs to pests, weather or harvest, another species fills the void maintaining full use of available resources.
- Enhance longevity through the addition of perennials that contain a thick canopy thus providing continual cover that can also protect the soil. Constant leaf fall builds organic matter and allows uninterrupted nutrition circulation. Dense, deep root systems of long-lived woody plants are an effective mechanism for nutrient capture offsetting the negative losses through leaching. Perennial vegetation also provides more habitat permanence and contributes to pest-enemy complexes.
- Introduce fallow periods to restore soil fertility through biologically mediated mechanisms, and to reduce agricultural pest populations as life cycles are interrupted with forest regrowth or legume-based rotations.
- Enhance additions of organic matter by including high biomass-producing plants. Accumulation of both 'active' and 'slow fraction' organic matter is key

for activating soil biology, improving soil structure and macroporosity and elevating the nutrient status of soils. Moreover, organic matter forms the foundation of complex food webs, which influence the abundance and diversity of natural enemies.

- Increase landscape diversity by promoting a mosaic of agroecosystems representative of various stages of succession. Risk of complete failure is spread among, as well as within, the various cropping systems. Improved pest control is also linked to spatial heterogeneity at the landscape level.

When properly implemented, diversification strategies lead to the establishment of the desired type of plant, insect and soil biodiversity and the ecological infrastructure necessary for attaining optimal pest control and soil fertility. As emphasized in this chapter, it is important to ensure that above ground diversification schemes are complemented by soil organic management, as both above and below ground biodiversity together form the pillars of agroecosystem health.

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