

An agroecological basis for designing diversified cropping systems in the tropics

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In: New Dimensions in Agroecology. D. R. Clements and A. Shrestha (Eds). Haworth Press, N. Y. 2004.

SUMMARY. Small scale diversified systems which mostly rely on local resources and complex crop arrangements, are reasonably productive and stable, exhibiting a high return per unit of labor and energy. In many ways complex polycultures and agroforestry systems used by small tropical farmers mimic the structure and function of natural communities therefore acquiring many features typical of such communities, such as tight nutrient cycling, resistance to pest invasion, vertical structure, and high levels of biodiversity.

An agroecological approach to improve tropical small farming systems must ensure that promoted systems and technologies are suited to the specific environmental and socio-economic conditions of small farmers, without increasing risk or dependence on external inputs. Rather, agroecological development projects should incorporate elements of traditional agricultural knowledge and modern agricultural science, featuring resource-conserving yet highly productive systems such as polycultures, agroforestry, and the integration of crops and livestock.

It is ecologically futile to promote mechanized monocultures in areas of overwhelming biotic intricacy where pests flourish year-round and nutrient leaching is a major constraint. Here, it pays to imitate natural cycles rather than struggle to impose simplistic ecosystems that are inherently complex. For this reason, many researchers think that successional ecosystems can be particularly appropriate templates for the design of sustainable tropical agroecosystems.

INTRODUCTION

Of all the regions where agriculture is practiced, the tropics are where novel production approaches are most urgently needed. This region has not benefited significantly from modern technologies which led to high agricultural productivity in the temperate regions. Abundant rainfall and high temperatures promote competition from weeds, pest outbreaks and nutrient leaching; constraints that constantly plague the large-scale plantations and annual crop monocultures that cover large areas in the tropics (Beets, 1990).

In many tropical areas, agriculture is highly mechanized and has implied the simplification of the structure of the environment over vast areas, replacing nature's diversity with a small number of cultivated plants and domesticated animals. Genetically, monocultures are shockingly dependent on a handful of crop varieties. Researchers have repeatedly warned about the extreme vulnerability associated with this genetic uniformity, claiming that ecological homogeneity in agriculture is closely linked to pest invasions (Adams, Ellingbae and Rossineau, 1971; Robinson, 1996). Many scientists argue that the drastic narrowing of cultivated plant diversity has put tropical food production in greater peril. In vain, farmers have tried to overcome these biotic constraints typical of the less seasonal tropics by applying large amounts of chemical fertilizers and pesticides, but this approach has been limited by scarce and expensive

fossil fuels, but mostly by ecological backlash in the form of significant environmental and health externalities (Conway, 1997).

On the other hand, small farmers, especially those living in more marginal environments, and whom were bypassed by agricultural modernization have not relied on agrochemicals to sustain production. Although estimates vary considerably, about 1.9-3.3 billion rural people in the developing world remain directly untouched by modern agricultural technology. The great majority of these people are peasants, indigenous people and small family farmers, who mostly still farm the valleys and slopes of rural landscapes with traditional and/or subsistence methods. About 370 million of these, are extremely poor people whose livelihoods depend on the vast, diverse, and risk prone marginal environments in the south (Conway, 1997). Most of these people cultivate in small scale diversified systems which rely on local resources and complex crop arrangements. Research has shown that such systems are reasonably productive and stable, exhibiting a high return per unit of labor and energy (Netting, 1993). For example, in Latin America, peasant production units reached about 16 million in the late 1980s occupying close to 60.5 million hectares, or 34.5% of the total cultivated land which reaches about 175 million hectares (DeGrandi, 1996). The peasant population includes 75 million people representing almost two thirds of the Latin America's total rural population (Ortega, 1986). Average farm size of these units is about 1.8 hectares, although the contribution of peasant agriculture to the general food supply in the region is significant. In the 1980s it reached approximately 41% of the agricultural output for domestic consumption, and is responsible for producing at the regional level 51% of the maize, 77% of the beans, and 61% of the potatoes.

Searching for ways to develop a more sustainable agroecosystems, several researchers have posited that tropical agroecosystems should mimic the structure and function of natural communities, (a practice followed by thousands of indigenous farmers for centuries), as these systems exhibit tight nutrient cycling, resistance to pest invasion, vertical structure and preserve biodiversity (Ewel, 1986; Soule and Piper, 1992).

If such ecological approach is used, it is important to ensure that promoted systems and technologies are suited to the specific environmental and socio-economic conditions of small farmers, without increasing risk or dependence on external inputs. Rather, agroecological development projects should feature resource-conserving yet highly productive systems such as polycultures, agroforestry and the integration of crops and livestock (Altieri, 1995).

The ecological futility of promoting mechanized monocultures in tropical areas of overwhelming biotic intricacy where pests flourish year-round and nutrient leaching is a major constraint has been amply demonstrated (Browder, 1989). A more reasonable approach is to imitate natural cycles rather than struggle to impose horticultural simplicity in ecosystems that are inherently complex. Ewell (1986) argues that successional ecosystems can be particularly appropriate templates for the design of sustainable tropical agroecosystems. Building on this idea and the contributions of modern agroecology, we provide principles for agroecosystem design emphasizing the development of cropping systems that enhance nutrient capture, and confer associational resistance to pests, thus reducing agroecosystem vulnerability while providing biological stability and productivity.

COMPARING NATURAL AND AGRICULTURAL ECOSYSTEMS

Many agroecologists have argued that by understanding the structural and functional differences between natural systems and agroecosystems we can learn much about the underlying processes that make crop systems more vulnerable to insect pests, dependent on external inputs, and inefficient in the use of local resources (Carol, Vandermeer and Rosset, 1990).

The dominant components of an agroecosystem are plants (and animals) selected, propagated, tended, and harvested by humans for the purpose of food and fiber production. In comparison to unmanaged systems, the composition and structure of agroecosystems is simple. The plant biomass is composed of stands usually dominated by one major crop plant within well-defined field boundaries.

The net result is an artificial monoculture system 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 (Cox and Atkins, 1974).

Human manipulation and alteration of ecosystems for the purpose of establishing agricultural production makes agroecosystems structurally and functionally very different from natural ecosystems (Table 1). Agroecosystems are artificial ecosystems that are solar powered, as are natural ecosystems, but differ in that (1) the auxiliary energy sources that enhance productivity are processed fuels (along with animal and human labor) rather than natural energies; (2) diversity is greatly reduced by human management in order to maximize yield of specific food and other products; (3) the dominant plants and animals are under artificial rather than natural selection; and (4) control is external and goal oriented rather than internal via subsystem feedback as in natural ecosystems (Gliessman, 1998).

Perhaps of major significance in relation to the instability of tropical monocultures are the following processes that alter ecosystem structure and function:

Landscape and field simplification

With agriculture the original flora and fauna are completely replaced over a vast area decreasing habitat heterogeneity. Where patches of natural vegetation persist they often occur on sites unsuitable for agriculture and contribute only minimally to the ecological stability of the area. As biological diversity is reduced, trophic structures tend to become simplified, and many niches are left unoccupied (Thies and Tschardtke, 1999). The danger of increased invasions and catastrophic pest or disease outbreaks is high, despite the intensive human input in the form of agrochemicals.

Monocultures are unfavorable environments for natural enemies of pests, due to high levels of disturbance and lack of ecological infrastructure the capacity. The capacity of predators and parasites to control invaders is lower than in more diverse agroecosystems (Landis, Wratten and Gurr, 2000). Most agroecologists agree that due to their reduced structural and functional diversity in relation to natural ecosystems, agroecosystems have lower resiliency than natural ecosystems.

Disruption of succession

Intensive agriculture prevents normal succession from taking place. Every newly planted crop represents the first stage of succession that is neither persistent nor steady state. The objective of growing a crop is to obtain the greatest possible harvest. Constant disturbance keeps the agroecosystem at the early stages of succession, where a greater proportion of gross productivity is available as net productivity or harvestable biomass. To maintain a system of this type, it is necessary for humans to assume responsibility for the costs of maintenance and regulation normally taken care of by the natural processes that lead to the establishment of a climax ecosystem.

Lowering of plant defenses

In natural ecosystems the assemblage of organisms is the result of natural selection and coevolution. Agroecosystems consist of unnatural assemblages of human selected domesticated species and an assortment of native or imported opportunistic species that manage to invade the site. These two groups have not been integrated into a steady-state system by the process of coevolution, and many opportunistic species frequently become weed, insect, and disease pests that must be dealt with by the farmer.

Throughout the crop domestication process, humans tended to select plants with fewer morphological and chemical defenses. Such intense human selection for rapid growth and high reproductive output resulted in a general lowering of the plants' allocation to defense. Of course, significant amounts of toxic secondary compounds remain in many edible crops, but the general trend has been the gradual reduction of those chemicals and morphological features that protected plants from arthropod herbivores. This often left the plants more vulnerable than their wild relatives, and it largely explains the widespread belief that there are more outbreaks of insects in agroecosystems than natural ecosystems (Altieri, 1994).

Inefficient nutrient cycling

Recycling of nutrients is minimal in most agroecosystems and considerable quantities are lost from the system with the harvest or as a result of leaching or erosion due to a great reduction in permanent biomass levels held within the system. Lower levels of organic matter accumulation and reduced biological activity in monoculture is also a key factor explaining soil fertility in deeply weathered and leached tropical soils. The frequent exposure of bare soil between cropping seasons also creates "leaks" of nutrients from the system. Instead of using locally recycled nutrients, farmers have come to rely heavily on petroleum-based nutrient inputs to replace these losses (Magdoff, 1992).

BUILDING ON TRADITIONAL AGRICULTURE

Many agricultural scientists have argued that the starting point in the development of new pro-poor agricultural development approaches are the very systems that traditional farmers have developed and/or inherited throughout centuries. Such complex farming systems, adapted to the local conditions, have helped small farmers to sustainably manage harsh environments and to meet their subsistence needs, without depending on mechanization, chemical fertilizers, pesticides or other technologies of modern agricultural science (Denevan, 1995). The persistence of millions of hectares under traditional agriculture in the form of raised fields, terraces, polycultures,

agroforestry systems, etc., document a successful indigenous agricultural strategy and comprises a tribute to the “creativity” of small farmers throughout the developing world (Wilken, 1997). These microcosms of traditional agriculture offer promising models for other areas as they promote biodiversity, thrive without agrochemicals, and sustain year-round yields. It is estimated that about 50 million individuals belonging to about 700 different ethnic indigenous groups live and utilize the humid tropical regions of the world. About two million of these live in the Amazon and southern Mexico (Toledo, 2000). In Mexico, half of the humid tropics is utilized by indigenous communities and “ejidos” featuring integrated agriculture-forestry systems aimed at subsistence and local regional markets.

Traditional farming systems commonly support a high degree of plant diversity in the form of polycultures and/or agroforestry patterns (Gliessman, 1998). This strategy of minimizing risks by planting several species of plants and varieties of crops stabilizes yields over the long term, promotes diet diversity and maximizes returns even under low levels of technology and limited resources (Harwood, 1979).

Most peasant systems are productive despite their low use of chemical inputs. Generally, agricultural labor has a high return per unit of input. The energy return to labor expended in a typical peasant farm is high enough to ensure continuation of the present system. Also in these systems, favorable rates of return between inputs and outputs in energy terms are realized. For example, on Mexican hillsides, maize yields in hand-labor dependent swidden systems are about 1940 kg/ha, exhibiting an output/input ratio of 11:1. In Guatemala, similar systems yield about 1066 kg/ha of maize, with an energy efficiency ratio of 4.84. When animal traction is utilized, yields do not necessarily increase but the energy efficiency drops to values ranging from 3.11-4.34. When fertilizers and other agrochemicals are utilized, yields can increase to levels of 5-7 t/ha, but energy ratios start exhibiting inefficient values (less than 2.0) (Netting, 1993).

In most multiple cropping systems developed by smallholders, productivity in terms of harvestable products per unit area is higher than under sole cropping with the same level of management (Francis, 1996). Yield advantages can range from 20 to 60% and accrue due to reduction of pest incidence and more efficient use of nutrients, water and solar radiation.

Undoubtedly, the ensemble of traditional crop management practices used by many resource-poor farmers represent a rich resource for modern workers seeking to create novel agroecosystems well adapted to the local agroecological and socioeconomic circumstances of peasants. Peasants use a diversity of techniques, many of which fit well to local conditions. The techniques tend to be knowledge-intensive rather than input-intensive, but clearly not all are effective or applicable, therefore modifications and adaptations may be necessary. The challenge is to maintain the foundations of such modifications grounded on peasants’ rationale and knowledge.

An example of this is efforts to develop alternatives to “slash and burn.” Slash and burn is perhaps one of the best examples of an ecological strategy to manage agriculture in the tropics. By maintaining a mosaic of plots under cropping and some in fallow, farmers capture the essence of natural processes of soil regeneration typical of any ecological succession. These systems however are reaching their limits for a variety of reasons. By understanding the rationale of the slash and burn, a contemporary discovery, the use of “green manures,” has provided an ecological pathway to the

intensification of the “milpa,” in areas where long fallows are not possible anymore due to population growth, land scarcity or conversion of forest to pasture.

Experiences in Central America show that “mucuna” based maize systems are fairly stable allowing respectable yield levels (usually 2-4 t/ha) every year. In particular, the system appears to greatly diminish drought stress because the mulch layer helps conserve water in the soil profile. With enough water around, nutrients are made readily available, in good synchronization with major crop uptake. In addition, the mucuna suppresses weeds, either because velvetbean physically prevents them from germinating and emerging or from surviving very long during the velvetbean cycle, or because a shallow rooting of weeds in the litter layer-soil interface makes them easier to control. Data shows that this system grounded in farmers knowledge, involving the continuous annual rotation of velvetbean and maize, can be sustained for at least fifteen years at a reasonably high level of productivity, without any apparent decline in the natural resource base (Buckles et al., 1998).

As illustrated with the “mucuna” system, an increased understanding of the agroecology and ethnoecology of traditional farming systems is necessary to continue developing contemporary systems. This can only occur from integrative studies that determine the myriad of factors that condition how farmers perceive their environment and subsequently how they modify it to later translate such information to modern scientific terms.

DESIGNING SUCCESSION ANALOG AGROECOSYSTEMS

As traditional farmers have done, natural successional communities can be used as models for agroecosystem design because they offer several traits of potential value to agriculture: (i) high resistance to pest invasion and attack, (ii) high retention of soil nutrients, (iii) enhanced agrobiodiversity and, (iv) reasonable productivity (Ewel, 1999).

As stated by Gliessman (1998) a major challenge in the tropics is to design agroecosystems that, on the one hand, take advantage of some of the beneficial attributes of the early stages of succession yet, on the other hand, incorporate some of the advantages gained by allowing the system to reach the later stages of succession. As shown in Table 2, only one desirable ecological characteristic of agroecosystems—high net primary productivity—occurs in the early stages of successional development; all the others do not become manifest until the later stages of development, an important reason to create more permanent agroecosystems through the inclusion of perennials.

Ecological principles for design

1. Increasing species diversity as this promotes fuller use of resources (nutrients, radiation, water, etc), protection from pests 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 it with 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. Crop mixtures also minimize risks especially by creating the sort of vegetative texture that controls specialist pests.

2. Enhance longevity through the addition of perennials that contain a thick canopy thus providing continual cover that protects the soil. Constant leaf fill builds organic matter and allows uninterrupted nutrient circulation. Dense, deep root systems of long-lived woody plants is an effective mechanism for nutrient capture offsetting the negative losses through leaching.
3. Impose a fallow to restore soil fertility through biomass accumulation and biological activation, and to reduce agricultural pest populations as life cycles are interrupted with a rotation of fallow vegetation and crops.
4. Enhance additions of organic matter by including legumes, biomass producing plants and incorporating animals. 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.
5. Increase landscape diversity by having in place 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.

MANAGEMENT OPTIONS FOR NATURAL SUCCESSION MIMICRY

Under a scheme of managed succession, natural successional stages are mimicked by intentionally introducing agricultural plants, animals, practices, and inputs that promote the development of interactions and connections between component parts of the agroecosystem. Plant species (both crop and noncrop) are planted that capture and retain nutrients in the system and promote good soil development. These plants include legumes, with their nitrogen-fixing bacteria, and plants with phosphorus-trapping mycorrhizae. As the system develops, increasing diversity, food web complexity, and level of mutualistic interactions all lead to more effective feedback mechanisms for pest and disease management. The emphasis during the development process is on building a complex and integrated agroecosystem with less dependence on external inputs.

There are many ways that a farmer, beginning with a recently cultivated field of bare soil, can allow successional development to proceed beyond the early stages. One general model is to begin with an annual monoculture and progressing to a perennial tree crop system, as follows (Gliessman, 1998):

- 1-2 year: The farmer begins by planting a single annual crop that grows rapidly, captures soil nutrients, gives an early yield, and acts as a pioneer species in the developmental process.
- 3 year: As a next step (or instead of the previous one), the farmer can plant a polyculture of annuals that represent different components of the pioneer stage. The species would differ in their nutrient needs, attract different insects, have different rooting depths, and return a different proportion of their biomass to the soil. One might be a nitrogen-fixing legume. All of these early species would contribute to the initiation of the recovery process, and they would modify the environment so that non-crop plants and animals—especially the macro- and microorganisms necessary for developing the soil ecosystem—can also begin to colonize.

- 4 year: Following the initial stage of development, short-lived perennial crops can be introduced. Taking advantage of the soil cover created by the pioneer crops, these species can diversify the agroecosystem in important ecological aspects. Deeper root systems more organic matter stored in standing biomass, and greater habitat and microclimate diversity all combine to advance the successional development of the agroecosystem.
- 5 year: Once soil conditions improve sufficiently, the ground is prepared for planting longer-lived perennials, especially orchard or tree crops, with annual and short-lived perennial crops maintained in the areas between them. While the trees are in their early growth, they have limited impact on the environment around them. At the same time, they benefit from having annual crops around them, because in the early stages of growth they are often more susceptible to interference from aggressive weedy species that would otherwise occupy the area.
- 6 year: As the tree crops develop, the space in between them can continue to be managed with annuals and short-lived perennials.
- 7 year and beyond: Eventually, once the trees reach full development, the end point in the developmental process is achieved. This last stage is dominated by woody plants which are key to the site-restoring growers of fallow vegetation because of their deep, permanent root systems.

Once a successional developed agroecosystem has been created, the problem becomes one of how to manage it. The farmer has three basic options:

- Return the entire system to the initial stages of succession by introducing a major disturbance, such as clear-cutting the trees in the perennial system. Many of the ecological advantages that have been achieved will be lost and the process must begin anew.
- Maintain the system as a perennial or tree crop agroecosystem.
- Reintroduce disturbance into the agroecosystem in a controlled and localized manner, taking advantage of the dynamics that such patchiness introduces into an ecosystem. Small areas in the system can be cleared, returning those areas to earlier stages in succession, and allowing a return to the planting of annual or short-lived crops. If care is taken in the disturbance process, the belowground ecosystem can be kept at a later stage of development, whereas the aboveground system can be made up of highly productive species that are available for harvest removal.

One example of a crop successional design comes from Costa Rica where researchers conducted spatial and temporal replacements of wild species by botanically/structurally/ecologically similar cultivars. Successional members for the natural system such as *Heliconia* spp, cucurbitaceous vines, *Ipomoea* sp, 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) formed an additional stratum, thus maintaining a continuous crop cover, avoiding site degradation and nutrient leaching, and providing nutrients throughout the year (Ewel, 1999).

DIVERSIFICATION STRATEGIES

In the process of emulating nature's diversity, various strategies to restore agricultural diversity in time and space can be utilized (Altieri, 1994; Gliessman, 1998; Finch and Sharp, 1976; Francis, 1986; Nair, 1982; Pearson and Ison, 1987):

1. *Crop rotations*: Temporal diversity in the form of leguminous green manures are incorporated into cropping systems, providing crop nutrients and breaking the life cycles of several insect pests, diseases, and weed life cycles.
2. *Variety mixtures*: Increasing plant genetic diversity at the field level through the use of variety mixtures and/or multi-lines increases genetic heterogeneity, reducing the vulnerability of monoculture crops to diseases.
3. *Polycultures*: Complex cropping systems in which two or more crop species are planted within sufficient spatial proximity to result in competition or complementation, thus enhancing yields and minimizing risks.
4. *Agroforestry systems*: A system where trees are grown together with annual crops and/or animals, providing the benefits of perennials and resulting in enhanced, complementary relations between components while increasing multiple use of the agroecosystem.
5. *Cover crops*: The use of pure or mixed stands of legumes or other annual plant species under fruit trees for the purpose of providing soil cover, improving soil fertility, enhancing biological control of pests, and modifying the orchard microclimate.
6. *Animal integration through crop-livestock mixtures*, which aids in achieving high biomass output and optimal recycling.

All of the above forms of agroecosystem diversification strategies share in common the following features (Altieri, 1995):

- a.) Maintain high vegetative cover as an effective soil and water conserving measure, achieved through the use of no-till practices, mulch farming, and use of cover crops and other appropriate methods.
- b.) Provide a regular supply of organic matter through the addition of organic matter (plant biomass, manure, compost, and promotion of soil biotic activity) which serves as a source of nutrients and fuel to microbial populations.
- c.) Enhance nutrient recycling mechanisms through the use of systems based on legumes, trees, and incorporation of livestock.
- d.) Promote pest regulation through enhanced activity of biological control agents achieved by conserving natural enemies and antagonists through establishment of an ecological infrastructure associated to diversified cropping patterns.

The mechanisms that result in higher productivity in diverse agroecosystems are embedded in the process of facilitation. Facilitation occurs when one crop modifies the environment in a way that benefits a second crop, for example, by lowering the

population of a critical herbivore, or by releasing nutrients that can be taken up by the second crop (Vandermeer, 1989). Facilitation may result inoveryielding even where direct competition between crops is substantial. The combined effects or synergies of complex agroecosystems can best be understood when one examines the findings of research on the effects of plant diversity and soil fertility on insect pest populations:

Vegetational diversity and pest outbreaks

Experiments testing the theory that decreased plant diversity in agroecosystems leads to enhanced herbivorous insect abundance, have shown that mixing certain plant species with the primary host of a specialized herbivore gives a fairly consistent result: specialized insect pest species usually exhibit higher abundance in monoculture than in diversified crop systems (Altieri and Letourneau, 1982; Andow, 1991).

Several reviews have been published documenting the effects of within-habitat diversity on insects (Altieri, 1994). Two main ecological hypotheses (natural enemy hypothesis and the resource concentration hypothesis) have been offered to explain why insect communities in agroecosystems can be stabilized by constructing vegetational architectures that support natural enemies and/or directly inhibit pest attack. The literature is full of examples of experiments documenting that diversification of cropping systems often leads to reduced pest populations. Andow (1991) reviewed 150 published studies documenting the effects of agroecosystem diversification on insect pest abundance, examining 198 herbivore species in total. Fifty-three percent of these species were found to be less abundant in the more diversified system, 18% were more abundant in the diversified system, 9% showed no difference, and 20% showed a variable response.

Many of these studies have transcended the research phase and have found applicability to control specific pests such as the stemborers in Africa. Scientists at ICIPE developed a habitat management system which uses two kinds of crops that are planted together with maize: a plant that repels these borers (the push) and another that attracts (pulls) them (Khan et al., 1998). The push-pull system has been tested on over 450 farms in two districts of Kenya and has now been made available to the national extension systems in East Africa. Participating farmers in the breadbasket of Trans Nzoia are reporting a 15-20 percent increase in maize yield. In the semi-arid Suba district – plagued by both stemborers and striga – a substantial increase in milk yield has occurred in the last four years, with farmers now being able to support grade cows on the fodder produced. When farmers plant maize, napier and desmodium together, a return of US\$ 2.30 for every dollar invested is made, as compared to only \$1.40 obtained by planting maize as a monocrop. Two of the most useful trap crops that pull the borers' natural enemies are napier grass (*Pennisetum purpureum*) and Sudan grass (*Sorghum vulgare Sudanese*), both important fodder plants; these are planted in a border around the maize. Two excellent borer-repelling crops which are planted between the rows of maize are molasses grass (*Melinis minutifolia*), which also repels ticks, and the leguminous silverleaf, *Desmodium*, can suppress the parasitic weed, *Striga*, by a factor of 40 compared to maize monocrop; its N-fixing ability increases soil fertility; and it is an excellent forage. As an added bonus, sale of **Desmodium** seed is proving to be a new income-generating opportunity for women in the project areas.

It is clear that both empirical data and theoretical arguments suggest that differences in pest abundance between diverse and simple annual cropping systems can

be explained by differences in the movement, colonization and reproductive behavior of herbivores and by the activities of natural enemies. The studies further suggest that the more diverse the agroecosystems and the longer this diversity remains undisturbed, the more internal links develop to promote greater insect stability (Altieri and Nicholls, 1999). Research along these lines is crucial to a vast majority of small farmers who rely on the rich complex of predators and parasites associated with their mixed cropping systems for insect pest control. Any changes on the levels of plant diversity within such systems can lead to disruptions on pesticides. Regardless, more studies are needed to determine the underlying elements of plant mixtures that disrupt pest invasion and that favor natural enemies.

Integrating effects of soil management: Healthy soils – healthy plants

For resource-poor farmers, crop diversification strategies must be complemented by regular applications of organic amendments (crop residues, animal manures, and composts) to maintain or improve soil quality and productivity. Despite the fact that this is a common practice of tropical smallholders, little is known about the multifunctional effects of organic amendments on other agroecosystem components, beyond the documented effects on improved soil structure and nutrient content. Well-aged manures and composts can serve as sources of growth-stimulating substances, such as indole-3-acetic acid and humic and fulvic acids (Magdoff and van Es, 2000). Beneficial effects of humic acid substances on plant growth are mediated by a series of mechanisms, many similar to those resulting from the direct application of plant growth regulators.

The ability of a crop plant to resist or tolerate pests is tied to optimal physical, chemical and biological properties of soils. Adequate moisture, good soil tilth, moderate pH, right amounts of organic matter and nutrients, and a diverse and active community of soil organisms all contribute to plant health. Organic rich soils generally exhibit good soil fertility as well as complex food webs and beneficial organisms that prevent infection by disease-causing organisms such as *Pythium* and *Rhizoctonia*. On the other hand, farming practices such as high applications of nitrogen fertilizer can create nutrition imbalances, and render crops susceptible to diseases such as *Phytophthora* and *Fusarium* and stimulate outbreaks of Homopteran insects such as aphids and leafhoppers (Campbell, 1989). In fact, there is increasing evidence that crops grown in organic rich and biologically active soils are less susceptible to pest attack. Many studies suggest that the physiological susceptibility of crops to insect pests and pathogens may be affected by the form of fertilizer used (organic vs. chemical fertilizer).

The literature is abundant on the benefits of organic amendment additions that encourage resident antagonists thus enhancing biological control of plant diseases. Several bacteria species of the genus *Bacillus* and *Pseudomonas*, as well as the fungus *Trichoderma* are key antagonists that suppress pathogens through competition, lysis, antibiosis, and hyperparasitism (Palti, 1981).

Studies documenting lower abundance of several insect herbivores in low-input systems, have partly attributed such reduction to a low nitrogen content in organically farmed crops (Luna, 1988). In Japan, density of immigrants of the planthopper *Sogatella furcifera* was significantly lower while settling rates of female adults and survival rate of immature stages of ensuing generations were lower in organic rice fields. Consequently, the density of planthopper nymphs and adults in the ensuing generations decreased in

organically farmed fields (Kajimura, 1995). In England, conventional winter wheat fields developed a larger infestation of the aphid *Metopolophium dirhodum* than its organic counterpart. This crop also had higher levels of free protein amino acids in its leaves during June, which were believed to have resulted from a nitrogen top dressing of the crop early in April. However, the difference in the aphid infestations between crops was attributed to the aphid's response to relative proportions of certain non-protein to protein amino acids in the leaves at the time of aphid settling on crops (Kowalski and Visser, 1979). In greenhouse experiments, when given a choice of maize grown on organic versus chemically fertilized soils, European corn borer females preferred to significantly lay more eggs in chemically fertilized plants (Phelan, Maan and Stinner, 1995).

Such findings are of key importance to tropical resource-poor farmers such as Cakchiquel farmers in Patzum, Guatemala who have experienced increased pest populations (aphids and corn earworms) in maize since they abandoned organic fertilization and adopted synthetic fertilizers (Morales, Perfecto and Ferguson, 2001). Many farmers undergoing modernization may be facing similar impacts due to higher fertilizer use, which in turn may create subtle imbalances in the agroecology of specific farming systems.

CONCLUSIONS

Technological innovation in the tropics has been characterized by the transfer of agricultural systems from temperate regions without due consideration to their ecological fit. Monoculture agriculture (i.e. extensive grain and plantation crops) is basically a cultural baggage of early colonial times, which still make short-term economic sense, but in the long-term constitutes a total ecological mismatch. It is time to use ecological principles as part of the design criterion of agroecosystems, thus replacing what has become a strictly economic decision-making process with one that includes ecological ideas, and especially local farmers' perspectives (Vandermeer, 1995).

An important challenge is to apply such ideas to design new agroecosystems using nature as a model. Such mimics, like their models, can be productive, pest resistant and conservative of nutrients and other resources, and consequently more cost-effective and less risky to farmers, especially poor peasants. As discussed above, a key strategy for sustainable tropical agriculture is to reincorporate diversity into the agricultural landscape and manage it more effectively. Emergent ecological properties develop in diversified agroecosystems that allow the system to function in ways that maintain soil fertility, encourage pest regulation and sustain productivity.

Surely there are no simple links between species diversity and ecosystemic stability. Apparently functional characteristics of component species are as important as the total number of species. Recent studies with grassland plots conclude that functionally different roles represented by many plants are at least as important as the total number of species in determining processes and services in ecosystems (Tilman, Wedin and Knops, 1996). It is far easier to mimic specific ecosystem processes than to try to duplicate all the complexity of nature. All that is needed is to select the right kind of diversity (adding one or two plant species), to achieve herbivore resistance, enhanced productivity and nutrient supply.

The main limitation of promoting species-rich agroecosystems is that they are difficult to manage. The biggest challenge in managing a successional developed

system is to learn how to introduce disturbance in ways that stimulate system productivity on the one hand and, on the other, provide resistance to change the variation within the ecosystem. This can be done in many different ways depending on local environmental conditions, the structure of mature natural ecosystems normally present, and the feasibility of maintaining modifications of those conditions over the long term.

Some authors contend that there is a trade-off between high-diversity and low yield, and that farmers will always have to choose between systems that confer low risk, low productivity, and high productivity but high risk. According to Ewel (1986) the very attributes that make diverse agroecosystems attractive, seem to have biological costs that are incompatible with high yield.

The literature is somewhat divided on this issue, although a significant number of scientists highlight the overyielding advantages of polycultures and the multifunctionality of small and diversified farms (Francis, 1986; Vandermeer, 1989). The very practice of millions of small tropical farmers which favor polycultures, agroforestry and diversified patterns give credibility to a more agroecological approach. Regardless, the task at hand for tropical agroecologists will be to design complex agroecosystems that simultaneously sustain harvestable products and ecological functions.

Given a range of economic and environmental circumstances, it is possible that for capitalized farmers with access to inputs, a relatively simple rotation or intercrop may be all that is needed. For resource-poor farmers, where crop failure cannot be tolerated, diverse cropping systems should be the agroecosystem of choice. Whatever the preferred system, diversity will be of value in a large or small-scale agroecosystem for a variety of reasons (Altieri, 1994; Gliessman, 1998):

- As diversity increases, so do opportunities for coexistence and beneficial interactions between species that can enhance agroecosystem sustainability.
- Greater diversity often allows better resource-use efficiency in an agroecosystem. There is better system-level adaptation to habitat heterogeneity, leading to complementarity in crop species needs, diversification of niches, overlap of species niches, and partitioning of resources.
- Ecosystems, in which plant species are intermingled, possess an associated resistance to herbivores. As in diverse systems, there is a greater abundance and diversity of natural enemies of pest insects, keeping in check the populations of individual herbivore species.
- A diverse crop assemblage can create a diversity of microclimates within the cropping system that can be occupied by a range of noncrop organisms – including beneficial predators, parasites, pollinators, soil fauna and antagonists – that are of importance for the entire system.
- Diversity in the agricultural landscape can contribute to the conservation of biodiversity in surrounding natural ecosystems.
- Diversity in the soil performs a variety of ecological services such as nutrient recycling and detoxification of noxious chemicals and regulation of plant growth.

- Diversity reduces risk for farmers, especially in marginal areas with more unpredictable environmental conditions. If one crop does not do well, income from others can compensate.

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Table 1. Structural and functional differences between natural ecosystems and agroecosystems (modified after Gliessman, 1998).

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

Table 2. Desirable ecological characteristics of agroecosystems in relation to successional development (after Gliessman 1998):

Successional stage of greatest development

Characteristic	Early	Middle	Late	Benefit to agroecosystem
High species diversity				Reduced risk of catastrophic crop loss
High total biomass				Larger source of soil organic matter
High net primary productivity				Greater potential for production of harvestable biomass
Complexity of species interactions				Greater potential for biological control
Efficient nutrient cycling				Diminished need for external nutrient inputs
Mutualistic interference				Greater stability; diminished need for external inputs