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Developing Sustainable Agroecosystems

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Yields in modern agricultural systems are sustained by investing costly external resources of uncertain future availability and with technologies that have prompted ecosystemic degradation. The ecological and socioeconomic aspects of developing alternative, self-sustained, energy efficient, less resource-intensive agroecosystems are analyzed. *(Accepted for publication 13 August 1982)*

Since its beginning, agriculture has tested the resiliency of nature. Natural communities have been replaced with artificially supported, productive communities. Agriculture's objectives generally have been to achieve maximum yields, operate with a maximum profit, minimize year-to-year instability in production, and prevent long-term degradation of the productive capacity of the agricultural system (Watt 1973). Theoretically, these objectives should be compatible and mutually reinforcing. Unfortunately, developments in agriculture have removed the crop ecosystems from their parent nonagricultural ecosystems (Potts and Vickerman 1974) to the extent that agroecosystems and natural ecosystems have become strikingly different in structure and function (Table 1).

The maintenance of an imposed order of simplified agricultural systems against the natural tendency toward entropy, diversity, and stability demands energy and resources (Turnbull 1969). The depletion of nutrients, loss of soil fertility, and the alteration of soil structure must be compensated for by large subsidies of fertilizer and soil conditioners. Similarly, pesticides must be applied to compensate for the lack of self-regulating mechanisms in monocultures (Root 1973). The large-scale structural changes that have been made in agriculture include the creation of large, specialized farms, increased mechanization and use of biochemicals, regional specialization of production, and increased interregional marketing (Buttel 1980a,b).

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Modern farming has thus become a highly complex activity, where gains in crop yield depend directly on intensive management and on the uninterrupted availability of supplemental energy and resources. This approach is no longer appropriate in an energy-troubled era; therefore, progress towards a more self-sustained, energy-efficient agriculture is desirable. However, 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 those of inadequate credit, technology, education, political support, and access to public service. Social complications, rather than technical ones, are likely to be the major barriers against any transition from high capital/energy production systems, to labor-intensive, low energy-consuming agricultural systems (Janzen 1973).

Modern agriculturalists had assumed that the agroecosystem/natural ecosystem dichotomy need not lead to undesirable consequences, yet, unfortunately, a number of "ecological diseases" (Gastó 1980) have been associated with the intensification of food production. They may be grouped into two categories (Alexander 1974, Gastó 1978, Pimentel et al. 1973, 1980): diseases of the ecotope, which include erosion, loss of soil fertility, depletion of nutrient reserves, salinization and alkalinization, loss of fertile croplands to urban development, and diseases of the biocoenosis, which include loss of crop, wild plant, and animal genetic resources, elimination of natural enemies, pest resurgence and genetic resistance to pesticides, chemical contamination, and destruction of natural control mechanisms. Under conditions of intensive management, treatment of such "diseases" requires an increase in the external costs to the extent that, in some agricultural systems, the amount of energy invested to produce a desired yield surpasses the energy harvested (Cox and Atkins 1979).

RESTORING ECOLOGICAL HEALTH

To restore "ecological health" in agricultural systems energy and resource overuse should be curtailed, production methods that restore community stability should be employed, a maximum of organic matter and nutrients should be recycled, the best possible multiple use of the landscape should be made, and efficient energy flow should be ensured. Also, as much food as possible should be grown locally that is adapted to the local environment and local taste.

The technical development of such 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. Social reforms along these lines have the added benefits of increasing employment and reducing farmers' dependence on government and the pressures of credit demands and industry (Levins 1973).

We recognize that these proposed changes conflict with the Western capitalist 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 2 billion additional people by the close of this century. Each of these criticisms is valid if analyzed within the current socioeconomic frame-

work, but not so if we realize that the proposed sustainable agroecosystems represent profound changes that would have major social and political implications. We believe that most of the present and future problems of malnourishment and starvation are due more to patterns of food distribution and political economics than to agricultural limits or the type of technology used in food production.

GUIDELINES FOR ACHIEVING DYNAMIC STABILITY

Productivity in agricultural systems cannot be increased indefinitely. A ceiling is placed on potential productivity by the physiological limits of crops—the "carrying capacity" of the habitat and the external costs incurred from the efforts to enhance production. This point is the "management equilibrium" (Lewis 1959) where the ecosystem, considered to be in dynamic equilibrium with environmental and management factors, produces a sustained yield. The characteristics of this balanced management will vary with different crops, geographical areas, and management objectives, and, therefore, 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:

Primary Production

Depending on climatic and edaphic factors, each area is characterized by a type of vegetation that has a particular biomass production capacity. An area covered by natural grassland (i.e., of a standing crop value of 6600 g/m^2) is not able to support a forest (i.e., 26,000 g/m^2) unless external 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 by orchards.

Land Use Capability

Soils have been classified into eight land use capability groups, each determined by physicochemical factors—slope, water availability, etc. (USDA 1959). According to this classification, soils of class I and II have a high natural fertility, good texture and permeability, and are deep, erosion-resistant soils suitable for many types of crops. However, when trees and shrubs are replaced by wheat on the hillsides (i.e., class VI soil), the yields decline progressively and the soil becomes badly eroded (Gastó and Gastó 1970). Such major land qualities related to plant growth as availability of water, nutrients, and oxygen; soil texture and depth; salinization and/or alkalinization; possibilities for mechanization; and resistance to erosion are important in determining the suitability of a tract of land for a certain agricultural use (Vink 1975).

Vegetational Patterns

The natural vegetation of an ecosystem can be used as an architectural and botanical model for designing and structuring an agroecosystem to replace it. The study of productivity, species composition, efficiency of resource utilization, resistance to pests, leaf area distribution, etc. in natural plant communities is important for building agroecosystems that mimic the structure and function of natural successional ecosystems (Ewell 1979). In Costa Rica, Ewell et al. (unpublished data) conducted spatial and temporal replacements of wild species by botanically and/or 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 simulated by plantain, squash varieties, yams, sweet potatoes, local bean crops, *Cajanus cajan,* corn/sorghum/rice, papaya, cashew, and *Cassava* spp., respectively. By years two and three, fast-growing tree crops (i.e., Brazil nuts, peach, palm, rosewood, etc.) may form an additional stratum, thus maintaining a continual crop cover, avoiding site degradation and nutrient leaching and providing crop yields throughout the year (Uhl and Murphy 1981).

Gastó and Contreras (1972) designed a similar conversion system in the Mediterranean matorral 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. shrubs, a food source for the animals. Thus, species composition was altered, but the structural profile was left intact.

Knowledge of Local Farming Practices

In most rural areas farmers have been cultivating for decades. Some have failed and others have succeeded in developing adapted cropping systems. On small farms in the tropics, for example, farmers have successfully minimized risk and maximized return by intercropping, using low levels of technology and resources. Recent research on polycultures (Harwood 1979) has demonstrated that many characteristics of traditional agroecosystems are more desirable than those of monocultures. Generally, polycultures are more productive, utilize soil resources and photosynthetically active radiation more efficiently, resist pests, epidemics, and weeds better, produce more varied and nutritious food, better utilize local resources and nonhybrid, open-pollinated, locally adapted seeds, and contribute to economic stability, social equality, and farmers' direct partici-

Table 1. Structural and functional differences between natural ecosystems and agroecosystems*

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

*Modified from Odum 1969.

pation in decision making. Thus, although tropical small farmers have generally been confined to farming low-quality, marginal soils with little capital or institutional support (de Janvry 1981), their systems provide valuable information for the development of yield-sustaining systems.

The situation is similar for organic farmers in the US and Europe. Recent comparative studies of conventional and organic farming (Lockeretz et al. 1981, USDA 1980) have shown that many organic methods consume less fossil energy, cause less soil erosion, obtain equal profits in most cases, and ensure acceptable yields in the long term. It is not clear whether these yields would be sufficient to meet domestic and export demand.

REDUCING ENERGY USE IN FOOD PRODUCTION

During the last decade, agricultural scientists have become aware that it is important, not only to increase food production, but also 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 on only one crop production process and have not considered the whole ecosystem.

For the most part, the more integrated approaches are directed toward enhancing photosynthetic efficiency through improvement of plant architecture, use of C_4 plants or varieties with a high leaf-area index, adoption of efficient planting patterns, and hormonal stimulation of net photosynthesis; improving soil management through minimum tillage, use of living legume mulches, cover cropping, use of manures, enhancement of biological N_2 fixation, and use of mycorrhizae; managing water more efficiently through drip irrigation, mulching, and windbreaks; and managing pests in an ecologically sound manner. These technologies propose minor changes in one or two components of the system, leaving the stringent structure of the monoculture unchallenged, but without doing so, 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, etc.) a whole new set of management and design options emerge (Edens and Koening 1980). Of special relevance are those manipulations that can simultaneously affect several components of the system. For example, growers who adopt novel agronomic systems (i.e., multiple cropping or agroforestry systems) can achieve several crop management objectives simultaneously and sometimes require little if any fertilizer or pesticides to sufficiently protect crops and enhance soil fertility. By interplanting wild heliotrope *(Heliotropium europaeum)* within leguminous crops, weed populations have been reduced about 70% and the abundance of several insect pests reduced below an economic threshold as well (Putnam and Duke 1978). By introducing French and African marigolds 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 in agriculture along these lines provide a new context for agroecosystem management in which stability of the system depends on manipulating the ecological assemblage in fields to promote biotic interactions that benefit farmers.

MANIPULATION OF VEGETATIONAL DIVERSITY

The loss of diversity through the expansion of monocultures has encouraged soil erosion, nutrient depletion, inefficient use of water and energy, reduction of local wildlife, outbreaks of diseases and pests (Wilken 1977). Restoration of plant diversity through crop rotations, interplantings, agroforestry systems, and cover crops in orchards can correct several of these imbalances. Regional diversification of crop–field boundaries with windbreaks, shelterbelts, and living fences can improve habitat for wildlife and beneficial insects, provide sources of wood, medicinal plants, organic matter, resources for pollinating bees, and, in addition, modify wind speed and the microclimate.

Diversity and Nutrient Cycling

In interplanted agroecosystems the low disturbance and closed canopies promote water and nutrient conservation. Nutrient cycling tends to be rapid. For example, in an agroforestry system, minerals lost by annuals are rapidly taken up by perennial crop plants. In addition, the nutrient robbing propensity of some crops is counteracted by the enriching addition of organic matter to the soil by 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. In the tropics Ewell et al. (1983) found that increased diversity in cropping systems was associated with larger root area, which increases nutrient capture. The maintenance of root systems having large surface areas and an even distribution in the soil profile is desirable for agroecosystems in areas where soil-nutrient storage is often low and leaching rates are high.

Diversity and Plant Diseases

Monocultures are almost invariably prone to diseases. One of the various epidemiological strategies that can be applied to minimize losses due to plant diseases and nematodes is increasing 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 cowpea intercropped with cassava or plantain. The available examples indicate that mixtures of different 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, Moreno 1979). Certain associated plants can function as repellents, antifeedants, growth disrupters, or toxicants. In the case of soil-borne pathogens, some plant combinations and organic amendments can enhance soil fungistasis and antibiosis (Sumner et al. 1981).

Diversity and Weed Populations

The continuous manipulations of the physical environment necessary for modern crop production has favored the selection of opportunistic and highly competitive weeds. Most weed species are stimulated by regular disturbances in monocultures. Of the various 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 between them. 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/mungbean 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 component crops, their density, and the fertility of the soil.

Allelopathy, which is the inhibition of germination, growth, or metabolism of one plant due to the release of organic chemicals by another, is a process that may contribute to increasing the competitiveness of crops over coexisting weeds in mono- 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 oats accessions can inhibit germination and growth of weeds such as wild mustard, *Brassica* spp., and poppy (*Papaver rhoeas*) (Putnam and Duke 1978).

Diversity and Insect Populations

The exacerbation of most insect-pest problems has been associated with the spatial and temporal expansion of crop monocultures at the expense of the natural vegetation, thereby decreasing local habitat diversity (van Emden and Williams 1974). This simplification can seriously affect the abundance and efficiency of natural enemies, which depend on habitat complexity for sources of alternate prey/hosts, pollen and nectar, shelter, and nesting and overwintering sites (Root 1973).

Plant diversification of agroecosystems can increase environmental opportunities for natural enemies and, consequently, improve biological pest control (van den Bosch and Telford 1964). Agronomically, there are several ways to design species-rich cropping systems. Field-margin vegetation and/or within-field plant diversity can be manipulated by designing mixtures or polycultures of various temporal and spatial arrangements. In Colombia, one of us (Altieri et al. 1978) found that beans grown in dicultures with corn had 25% fewer leafhopper adults *(Empoasca kraemeri)* than monoculture beans, and population densities of the leafbeetle *(Diabrotica balteata)* were 45% lower in corn/bean plots than in bean monocultures. The incidence of the fall armyworm *(Spodoptera frugiperda)* was 23% lower in corn polycultures than in monocultures. Planting times in dicultures can also affect pest interactions. For example, further reductions in leafhopper and fall armyworm densities were achieved by establishing the companion crops 10–20 days before the target crop. The effects of some of these systems on the dynamics of insect populations have recently been discussed by Altieri et al. (1978), Bach (1980), and Risch (1980). The effects on insect dynamics of increasing weed diversity by using weedborders and alternate rows of weeds and crops, or by providing weeds in certain periods of the crop growth has been extensively reviewed by Altieri et al. (1977), Altieri and Whitcomb (1979), and Cromartie (1981); vegetation-management strategies for natural pest regulation have been discussed by Altieri and Letourneau (1983).

Diversity and Productivity

Commonly, a relative yield advantage is obtained from a polyculture versus a monoculture (Vandermeer 1981). 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 1 hectare of polyculture, using the same plant populations (Harwood 1974). This LER can be expressed as follows (Vandermeer 1981):

$$\text{LER} = \frac{\text{Px}}{\text{Kx}} + \frac{\text{Py}}{\text{Ky}}$$

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. If the LER is greater than 1, the polyculture "overyields." Corn-bean dicultures, corn-bean-squash tricultures, and most of the agroforestry systems with trees as overstory (for example, cacao and rubber) are examples of "overyielding" polycultures in the Latin American tropics (Francis et al. 1976, Hart 1974).

CONCLUSION

The central issue in sustainable agriculture is not achieving maximum yield; it is long-term stabilization. Sustaining agricultural productivity will require more than a simple modification of traditional ad hoc techniques. The development of self-sufficient, diversified, economically viable, small-scale agroecosystems come from novel designs of cropping and/or livestock systems managed with technologies adapted to the local environment that are within the farmers' resources (Loucks 1977). 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.

The requirements of sustainable agroecosystems clearly are not only biological or technical, but are also social, economic, and political and illustrate the requirements of a sustainable society. Ecological change in agriculture cannot be promoted without comparable changes in all other related areas of society. The final requirement for ecological agriculture is an attitude toward nature of coexistence, not of exploitation.

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