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Agroecology: the science of natural resource management for poor farmers in marginal environments

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Abstract

Throughout the developing world, resource-poor farmers (about 1.4 billion people) located in risk-prone, marginal environments, remain untouched by modern agricultural technology. A new approach to natural resource management must be developed so that new management systems can be tailored and adapted in a site-specific way to highly variable and diverse farm conditions typical of resource-poor farmers. Agroecology provides the scientific basis to address the production by a biodiverse agroecosystem able to sponsor its own functioning. The latest advances in agroecological research are reviewed in order to better define elements of a research agenda in natural resource management that is compatible with the needs and aspirations of peasants. Obviously, a relevant research agenda setting should involve the full participation of farmers with other institutions serving a facilitating role. The implementation of the agenda will also imply major institutional and policy changes. © 2002 Published by Elsevier Science B.V.

Keywords: Agroecology; Resource-poor farmers; Natural resource management; Marginal environments; Sustainable agriculture

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1. Introduction

Perhaps the most significant realization at the beginning of the 21st century is the fact that the areas in the developing world, characterized by traditional/subsistence agriculture, remain poorly served by the top-down transfer-of-technology approach, due to its bias in favor of modern scientific knowledge and its neglect of local participation and traditional knowledge. For the most part, resource-poor farmers gained very little from the Green Revolution (Pearse, 1980). Many analysts have pointed out that the new technologies were not scale-neutral. The farmers with the larger and better-endowed lands gained the most, whereas farmers with fewer resources often lost, and income disparities were often accentuated (Shiva, 1991). Not only were technologies inappropriate for poor farmers, but peasants were excluded from access to credit, information, technical support and other services that would have helped them use and adapt these new inputs if they so desired (Pingali et al., 1997). Although subsequent studies have shown that the spread of high-yielding varieties among small farmers occurred in Green Revolution areas where they had access to irrigation and subsidized agrochemicals, inequities remain (Lipton and Longhurst, 1989).

Clearly, the historical challenge of the publicly funded international agricultural research community is to refocus its efforts on marginalized farmers and agroecosystems and assume responsibility for the welfare of their agriculture. In fact many analysts (Conway, 1997; Blavert and Bodek, 1998) agree that in order to enhance food security in the developing world, the additional food production will have to come from agricultural systems located in coun-

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Table 1
Technological requirements of resource-poor farmers

Innovation characteristics important to poor farmers	Criteria for developing technology for poor farmers
Input saving and cost reducing	Based on indigenous knowledge or rationale
Risk reducing	Economically viable, accessible and based on local resources
Expanding toward marginal-fragile lands	Environmentally sound, socially and culturally sensitive
Congruent with peasant farming systems	Risk averse, adapted to farmer circumstances
Nutrition, health and environment improving	Enhance total farm productivity and stability

tries where the additional people will live in, and especially where the majority of the poor people are concentrated (Pinstrup-Andersen and Cohen, 2000). Even this approach may not be enough, as current World Trade Organization (WTO) policies force developing countries to open markets, which allows rich countries to jettison their overproduction at prices that are disincentives to local producers (Mander and Goldsmith, 1996).

An estimated 1.4 billion people live and work in the vast, diverse and risk-prone rainfed areas in the south, where their farming operations cannot benefit much from mainstream agricultural technologies. Their systems are usually located in heterogeneous environments too marginal for intensive agriculture and remote from markets and institutions (Wolf, 1986). In order to benefit the poor more directly, a natural resource management (NRM) approach must directly and simultaneously tackle the following objectives:

- Poverty alleviation;
- Food security and self-reliance;
- Ecological management of productive resources;
- Empowerment of rural communities;
- Establishment of supportive policies.

The NRM strategy must be applicable under the highly heterogeneous and diverse conditions in which smallholders live, it must be environmentally sustainable and based on the use of local resources and indigenous knowledge (Table 1). The emphasis should be on improving whole farming systems at the field or watershed level rather than the yield of specific commodities. Technological generation should be a demand-driven process meaning that research priorities should be based on the socioeconomic needs and environmental circumstances of resource-poor farmers (Blauert and Zadek, 1998).

The urgent need to combat rural poverty and to conserve and regenerate the deteriorated resource base of small farms requires an active search for new kinds of agricultural research and resource management strategies. Non-government organizations (NGOs) have long argued that a sustainable agricultural development strategy that is environmentally enhancing must be based on agroecological principles and on a more participatory approach for technology development and dissemination, as many agree that this may be the most sensible avenue for solving the problems of poverty, food insecurity and environmental degradation (Altieri et al., 1998).

To be of benefit to the rural poor, agricultural research and development should operate on the basis of a “bottom-up” approach, using and building upon the resources already available: local people, their knowledge and their autochthonous natural resources. It must also seriously take into consideration, through participatory approaches, the needs, aspirations and circumstances of smallholders (Richards, 1985).

The main objective of this paper is to analyze the latest advances in agroecological research and examine whether ecological approaches to agriculture can provide clear guidelines for addressing the technical and production needs of poor farmers living in marginal environments throughout the developing world.

2. Building on traditional knowledge

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 (Chambers, 1983). 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). Although many of these systems have collapsed or disappeared in many parts of the Third World, the stubborn persistence of millions of hectares under traditional agriculture in the form of raised fields, terraces, polycultures, agroforestry systems, etc. are living proof of a successful indigenous agricultural strategy and comprises a tribute to the "creativity" of small farmers throughout the developing world (Wilken, 1987). 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 (Brookfield and Padoch, 1994). 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 (*Zea mays*) yields in hand-labor-dependent swidden systems are about 1940 kg ha^{-1}, exhibiting an output/input ratio of 11:1. In Guatemala, similar systems yield about 1066 kg ha^{-1} 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 to 4.34. When fertilizers and other agrochemicals are utilized yields can increase to levels of 5–7 mg ha^{-1}, 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, 1986). 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 and can lead to the conservation and regeneration of the natural resource base, as illustrated by the study of Reij et al. (1996) of indigenous soil and water management practices in Africa. 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.

"Slash and burn" or "milpa" 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. By understanding the rationale of the "milpa", 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 or conversion of forest to pasture (Flores, 1989).

Experiences in Central America show that velvetbean, "mucuna" (*Mucuna pruriens*), based maize systems are fairly stable allowing respectable yield levels (usually 2–4 mg ha^{-1}) every year (Buckles et al., 1998). In particular, the system appears to greatly diminish drought stress because the mulch layer left by mucuna helps conserve water in the

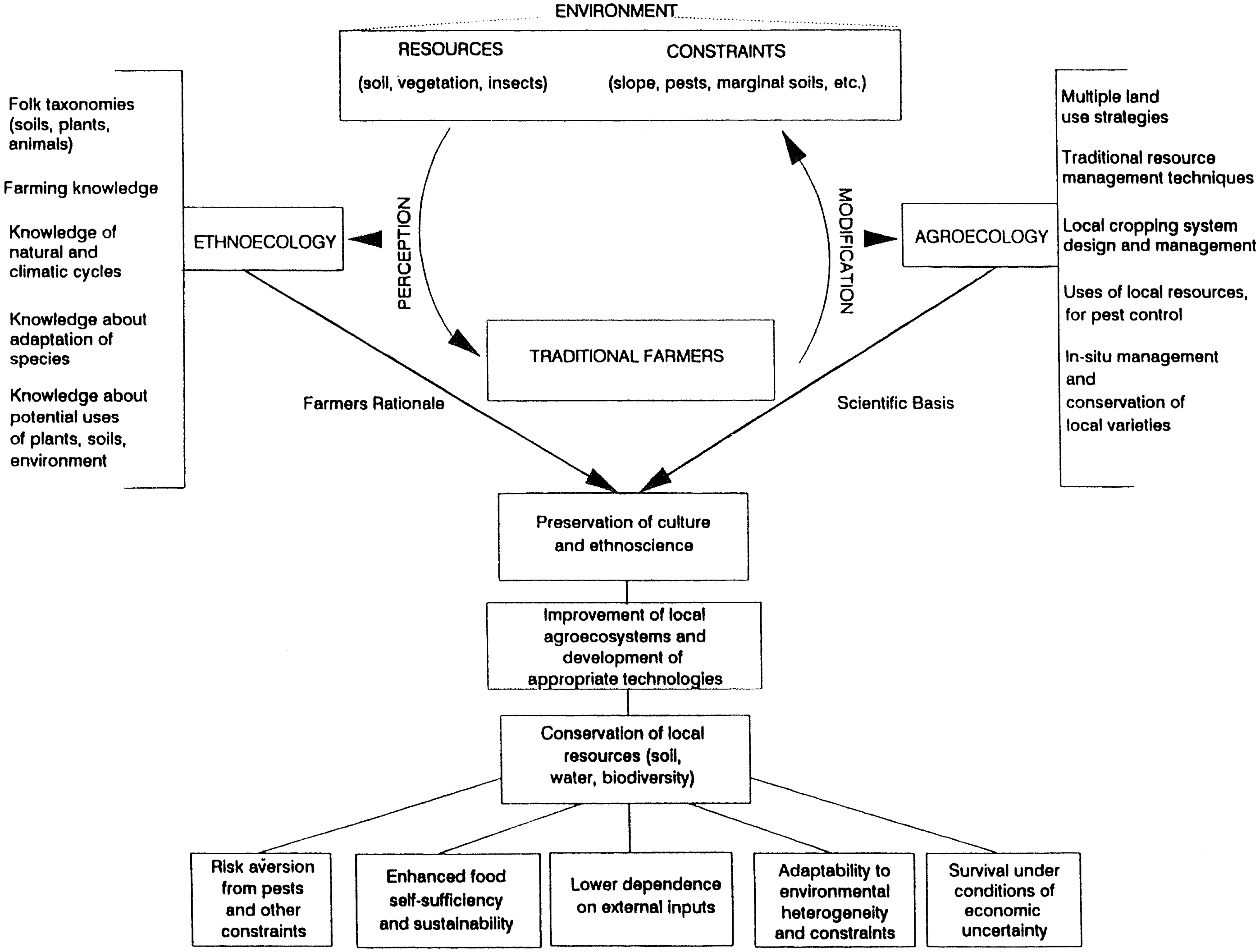


Fig. 1. The role of agroecology and ethnoecology in the retrieval of traditional farming knowledge and the development of sustainable agroecosystems, including appropriate innovations in pest management.

soil profile. With enough water around, nutrients are made readily available, in good synchronization with major crop uptake. In addition, the mucuna suppresses weeds (with a notable exception of one weed species, *Rottboellia cochinchinensis*), 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 15 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 (Fig. 1).

3. Defining the target population of a pro-poor NRM strategy

Although estimates of the number and location of resource-poor farmers vary considerably, it is estimated that about 1.9–2.2 billion people remain directly or indirectly untouched by modern agricultural technology (Pretty, 1995). In Latin America, the rural population is projected to remain stable at 125 million until the year 2000, but over 61% of this population are poor and are expected to increase. The projections for Africa are even more dramatic. The majority of the world's rural poor (about 370 million of the poorest) live in areas that are resource-poor, highly heterogeneous and risk-prone. Despite the increasing industrialization of agriculture, the great majority of the farmers are peasants, or small producers, who still farm the valleys and slopes of rural landscapes with traditional and subsistence methods. Their agricultural systems are small-scale, complex and diverse, and peasants are confronted to many constraints (Table 2). The worst poverty is often located in arid or semiarid zones, and in mountains and hills that are ecologically vulnerable (Conway, 1997). These areas are remote from services and roads and agricultural productivity is often low on a crop by crop basis, although total farm output can be significant. Such resource-poor farmers and their complex systems pose special research challenges and demand appropriate technologies (Netting, 1993).

4. Shifting the research focus

Natural resource problems experienced by poor farmers are not amenable to the research approaches previously used by the international research community. In most organizations, including the 16 international agricultural research centers associated to the Consultative Group on International Agricultural Research (CGIAR), research has been commodity-oriented with the goal of improving yields of particular food crops and livestock, but generally without adequately understanding the needs and options of the poor, nor the ecological context of the systems being addressed.

Most scientists use a disciplinary approach, often resulting in recommendations for specific domains and failing to equip farmers with appropriate technologies

Table 2
Some features and constraints of peasant farming systems and poor rural households

Characteristics of poor smallholders	Constraints to which poor farmers are exposed
Meager holdings or access to land	Heterogeneous and erratic environments
Little or no capital	Market failures
Few off-farm employment opportunities	Institutional gaps
Income strategies are varied and complex	Public good biases
Complex and diverse farming systems in fragile environments	Low access to land and other resources
	Inappropriate technologies

or empower them to make informed choices between available options. This situation is changing however as one of the Inter-Center Initiatives of the CGIAR is advocating a new approach to integrated natural resource management (INRM). The idea is to generate a new research approach that considers the interactive effects of ecosystems and socioeconomic systems at the ecoregional level (CGIAR, 2000). During a recent INRM workshop CGIAR scientists arrived at two major definitions of NRM (CGIAR, 2000):

A. Responsible and broad based management of land, water, forest and biological resource base (including genes) needed to sustain agricultural productivity and avert degradation of potential productivity.
B. Management of the biogeochemical processes that regulate the ecosystems within which agricultural systems function. NRM methods are those of system science, a system that embraces the interaction of humans with their natural resources.

Despite these new interdisciplinary efforts and the significant advances in understanding the links between components of the biotic community and agricultural productivity, agrobiodiversity is still treated as a “black-box” in agricultural research (Swift and Anderson, 1993). This calls for the need that crop, soil, water and pest management aspects be addressed simultaneously at the field or watershed level in order to match elements for production with forms of agroecosystem management that are sensitive to maintaining and/or enhancing biodiversity. Such integrated approach to agroecosystem management can allow the definition of a range of different strategies that can potentially offer farmers (especially those most reliant on the functions of agrobiodiversity) a choice of options or capacity to manipulate their systems according to their socioeconomic constraints and requirements (Blauert and Zadek, 1998).

A case in point has been the evolution of integrated pest management (IPM) and integrated soil fertility management (ISFM) which have proceeded separately without realizing that low-input agroecosystems rely on synergies of plant diversity and the continuing function of the soil microbial community, and its relationship with organic matter to maintain the integrity of the agroecosystem (Deugd et al., 1998). It is crucial for scientists to understand that most pest management methods used by farmers can also be considered soil fertility management strategies and that there are positive interactions between soils and pests that once identified, can provide guidelines for optimizing total agroecosystem function (Fig. 2). Increasingly, research is showing that the ability of a crop plant to resist or tolerate insect pests and diseases is tied to optimal physical, chemical and mainly biological properties of soils (Luna, 1988). Soils with high organic matter and active soil biological activity generally exhibit good soil fertility as well as complex food webs and beneficial organisms that prevent infection. On the other hand, farming practices that cause nutrition imbalances can lower pest resistance (Magdoff and van Es, 2000).

During the various INRM workshops, CGIAR scientists have been able to come up with a list of research themes relevant to less favorable areas (Table 3), but certainly that is not enough. In addition the CGIAR’s Technical Advisory Committee (TAC) came forward with a working proposal toward the goal of poverty reduction, food security and sustainable agriculture. As important as it is to define and map poverty, which appears to be the major emp-

Table 3
Examples of research themes for the lower-potential lands (Conway, 1997)

Improved understanding of selected critical agroecosystems such as the highland valleys of northern South Asia
New varieties produced through conventional breeding and genetic engineering that deliver higher yields in the face of environmental stress
Technologies for drought- and submergence-prone rain-fed rice cultivation
Small-scale, community-managed irrigation and water-conservation systems
More productive cereal-based farming systems in Eastern and Southern Africa
Improved agroeconomic systems appropriate to specific acid- and mineral-deficient soils in the savannahs of Latin America
Synergetic cropping and crop-livestock systems providing higher, more stable yields in the highlands of West Asia
Productive and sustainable agroforestry alternatives to shifting cultivation
Sustainable income- and employment-generating exploitation of forest, fisheries and natural resources

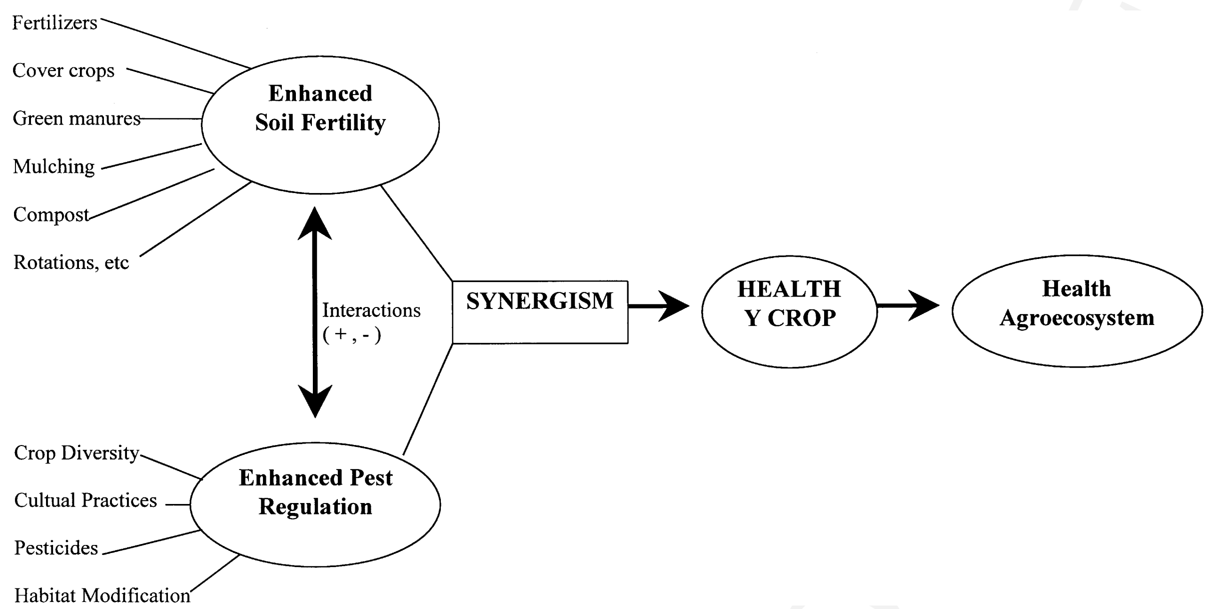


Fig. 2. Interactions of soil and pest management practices used by farmers, some of which may result in synergism leading to healthy and productive crop.

hasis of TAC, it is even more urgent to understand the root causes of poverty and tackle such factors head on through agricultural research. Another emphasis of TAC is to assess the impacts that unpredictable and extreme climatic events will have on the poor. Describing how long-term warming trends will affect small farm production, although important, is not as relevant as understanding the adaptability of agroecosystems on which the poor depend or how to enhance the resiliency of smallholders farming systems to climate change.

What is lacking in these new definitions is the explicit description of the scientific bases of NRM and of methods to increase our understanding of the structure and dynamics of agricultural and natural resource ecosystems and providing guidelines to their productive and sustainable management. A relevant NRM strategy requires the use of general agroecological principles and customizing agricultural technologies to local needs and circumstances. Where the conventional technology transfer model breaks down is where new management systems need to be tailored and adapted in a site-specific way to highly variable and diverse farm conditions. Agroecological principles have universal applicability but the technological forms through which those principals become operational depend on the prevailing environmental and socioeconomic conditions at each site (Uphoff, 2002).

5. Agroecology as a fundamental scientific basis for NRM

In trying to improve agricultural production, most scientists have disregarded a key point in the development of a more self-sufficient and sustaining agriculture: a deep understanding of the nature of agroecosystems and the principles by which they function. Given this limitation, agroecology has emerged as the discipline that provides the basic ecological principles for how to study, design and manage agroecosystems that are both productive and natural resource conserving, and that are also culturally sensitive, socially just and economically viable (Altieri, 1995).

Agroecology goes beyond a one-dimensional view of agroecosystems—their genetics, agronomy, edaphology, etc.—to embrace an understanding of ecological and social levels of co-evolution, structure and function. Instead of focusing on one particular component of the agroecosystem, agroecology em-

Table 4
Agoecosystem processes optimized through the use of agroecological technologies

Organic matter accumulation and nutrient cycling
Soil biological activity
Natural control mechanisms (disease suppression, biocontrol of insects, weed interference)
Resource conservation and regeneration (soil, water, germplasm, etc.)
General enhancement of agrobiodiversity and synergisms between components

phasizes the inter-relatedness of all agroecosystem components and the complex dynamics of ecological processes (Vandermeer, 1995).

Agroecosystems are communities of plants and animals interacting with their physical and chemical environments that have been modified by people to produce food, fiber, fuel and other products for human consumption and processing. Agroecology is the holistic study of agroecosystems, including all environmental and human elements. It focuses on the form, dynamics and functions of their interrelationships and the processes in which they are involved. An area used for agricultural production, e.g. a field, is seen as a complex system in which ecological processes found under natural conditions also occur, e.g. nutrient cycling, predator/prey interactions, competition, symbiosis, successional changes, etc. (Gliessman, 1998). Implicit in agroecological research is the idea that, by understanding these ecological relationships and processes, agroecosystems can be manipulated to improve production and to produce more sustainably, with fewer negative environmental or social impacts and fewer external inputs (Gliessman, 1998).

Ecological concepts are utilized to favor natural processes and biological interactions that optimize synergies so that diversified farms are able to sponsor their own soil fertility, crop protection and productivity. By assembling crops, animals, trees, soils and other factors in spatial/temporal diversified schemes, several processes are optimized (Table 4). Such processes are crucial in determining the sustainability of agricultural systems (Vandermeer et al., 1998).

Agroecology takes greater advantage of natural processes and beneficial on-farm interactions in order to reduce off-farm input use and to improve the efficiency of farming systems. Technologies emphasized tend to enhance the functional biodiversity of agroecosystems as well as the conservation of existing on-farm resources. Promoted technologies such as cover crops, green manures, intercropping, agroforestry and crop–livestock mixtures, are multi-functional as their adoption usually means favorable changes in various components of the farming systems at the same time (Gliessman, 1998).

Most of these technologies may function as an “ecological turntable” by activating and influencing components of the agroecosystem and processes such as:

1. Recycling of biomass and balancing nutrient flow and availability.
2. Securing favorable soil conditions for plant growth, through enhanced organic matter and soil biotic activity.
3. Minimizing losses of solar radiation, air, water and nutrients by way of microclimate management, water harvesting and soil cover.
4. Enhancing species and genetic diversification of the agroecosystem in time and space.
5. Enhancing beneficial biological interactions and synergisms among agrobiodiversity components resulting in the promotion of key ecological processes and services.

6. Challenging topics for agroecological research

6.1. Mimicking nature

At the heart of the agroecology strategy is the idea that an agroecosystem should mimic the functioning of local ecosystems thus exhibiting tight nutrient cycling, complex structure and enhanced biodiversity. The expectation is that such agricultural mimics, like their natural models, can be productive, pest-resistant and conservative of nutrients (Ewel, 1999).

This succession analog method requires a detailed description of a natural ecosystem in a specific environment and the botanical characterization of all potential crop components. When this information is available, the first step is to find crop plants that are structurally and functionally similar to the plants of the natural ecosystem. The spatial and chronological arrangement of the plants in the natural ecosystem are then used to design an analogous crop system (Hart, 1980). In Costa Rica, researchers conducted spatial and temporal replacements of wild species by botanically/structurally/ecologically similar cultivars. Thus, successional members of the natural system such as *Heliconia* spp., cucurbitaceous vines, *Ipomoea* spp., legume vines, shrubs, grasses, and small trees were replaced by plantain (*Musa* spp.), squash (*Curcurbita* spp.) varieties, and yams (*Dioscorea* spp.). By years 2 and 3, fast-growing tree crops (Brazil nuts (*Bertholletia excelsa*), peach (*Prunus persica*), palm (*Chamaerops* spp.), rosewood (*Dalbergia* spp.)) may form an additional stratum, thus maintaining continuous crop cover, avoiding site degradation and nutrient leaching, and providing crop yields throughout the year (Ewel, 1986).

According to Ewel (1999), the only region where it would be advantageous to imitate natural ecosystems rather than struggle to impose simplicity through high inputs in ecosystems that are inherently complex is the humid tropical lowlands. This area epitomizes environments of low abiotic stress but overwhelming biotic intricacy. The keys to agricultural success in this region are to (i) channel productivity into outputs of nutritional and economic importance, (ii) maintain adequate vegetational diversity to compensate for losses in a system simple enough to be horticulturally manageable, (iii) manage plants and herbivores to facilitate associational resistance, and (iv) use perennial plants to maintain soil fertility, guard against erosion, and make full use of resources. The idea however has also been proved in the temperate latitudes. Soule and Piper (1992) proposed utilizing the prairie of the US Great Plains as an appropriate model to develop an agroecosystem dominated by mixtures of perennial grasses, legumes and composites, all plants that differ in seasonal nutrient use and would thereby play complimentary and facilitating roles in the field. The use of perennial species would mimic the original prairie's soil-retaining, soil-building aspects. The legume component would help maintain an internal soil fertility supply and the diversity of crop species, including some native species, would allow development of natural checks and balances of herbivores, diseases and weeds. This natural systems agriculture (NSA) idea which was developed at The Land Institute in 1977 features an ecologically sound perennial food-grain-producing system where soil erosion goes to near zero, chemical contamination from agrochemicals plummets, along with agriculture's dependence on fossil fuels. A primary goal of NSA is to sufficiently *mimic the natural structure* to be *granted the function* of its components. Domesticating wild perennials and increasing seed yield and at the same time perennializing the major crops to be planted as domestic prairies is a major NSA strategy (Jackson, 2002).

To many, the ecosystem-analog approach is the basis for the promotion of agroforestry systems, especially the construction of forest-like agroecosystems that imitate successional vegetation, which exhibit low requirements for fertilizer, high use of available nutrients, and high protection from pests (Sanchez, 1995).

6.2. Understanding multi-species agroecosystems

In temperate or semiarid areas where complex natural ecosystems are not present as a model, the main strategy lies in the use of agroecological principles as part of the design criterion, thus replacing what has become a strictly economic decision-making process with one that also includes ecological ideas (Altieri et al., 1983).

Recent ecological research indicates that diverse natural communities are indeed more productive than simple systems (Tilman et al., 1996), just as many agricultural studies have shown that complex, multi-species agricultural systems are more dependable in production and more sustainable in terms of resource conservation than simplified agroecosystems (Vandermeer et al., 1998). Significant yield increases have been reported in diverse cropping systems compared to monocultures (Francis, 1986; Vandermeer, 1989). Enhanced yields in diverse cropping systems may result from a variety of mechanisms such as more efficient use of resources (light, water, nutrients) or reduced pest damage. Intercropping, which breaks down the monoculture structure, can provide pest control benefits, weed control advantages reduced wind erosion, and improved water infiltration (Francis, 1986).

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, e.g. 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 in overyielding even where direct competition between crops is substantial. Ecological studies suggest that more diverse plant communities are more resistant to disturbance and more resilient to environmental perturbations like drought (Tilman et al., 1996). In agricultural situations this means that polycultures exhibit greater yield stability and less productivity declines during a drought than in the case of monocultures. Natarajan and Willey (1996) examined the effect of drought on enhanced yields with polycultures by manipulating water stress on intercrops of sorghum (*Sorghum bicolor*) and peanut (*Arachis* spp.), millet (*Panicum* spp.) and peanut, and sorghum and millet. Although total biomass production in both polycultures and monocultures decreased as water stress increased, all of these intercrops overyielded consistently at five levels of moisture availability, ranging from 297 to 584 mm of water applied over the cropping season. Quite interestingly, the rate of overyielding actually increased with water stress such that the relative differences in productivity between monocultures and polyculture became more accentuated as stress increased.

Surveys conducted in hillsides after Hurricane Mitch in Central America showed that farmers using sustainable practices such as cover crops, intercropping and agroforestry suffered less damage than their conventional neighbors. The survey, spearheaded by the Campesino a Campesino movement, mobilized 100 farmer–technician teams and 1743 farmers to carry out paired observations of specific agroecological indicators on 1804 neighboring, sustainable and conventional farms. The study spanned 360 communities and 24 departments in Nicaragua, Honduras and Guatemala. Sustainable plots had 20–40% more topsoil, greater soil moisture, less erosion and experienced lower economic losses than their conventional neighbors (Holt-Gimenez, 2001). These data are of great significance to resource-poor farmers living in marginal environments and should provide the basis for an NRM strategy that privileges the temporal and spatial diversification of cropping systems as this leads to higher productivity and likely to greater stability and ecological resiliency.

6.3. Integrating effects of soil management: healthy soils–healthy plants

As emphasized earlier, 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. Much is known about the benefits of multi-species rotations, cover crops, agroforestry and intercrops (Francis, 1986). Less well known are the multifunctional effects of organic amendments 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* (Hendrix et al., 1990). Composts may alter resistance of plants to disease. Trankner (1992) observed that powdery mildew of wheat (*Triticum* spp.) and barley (*Hordeum* spp.) was less severe in compost—amended than in unamended soils. He also reported lower incidence of early blight and bacterial spot of tomato (*Lycopersicon esculentum*) field-grown plants in compost-amended soil than in the control. A number of pathogenic nematodes can also be suppressed with the application of organic amendments (Rodriguez-Kabana, 1986). On the other hand, farming practices such as high applications of N fertilizer can create nutrition imbalances, and render crops susceptible to diseases such as *Phytophtora* and *Fusarium* and stimulate outbreaks of Homopteran insects such as aphids and leafhoppers (Slansky and

Rodriguez, 1987). In fact there is increasing evidence that crops grown in organic-rich and biologically active soils are less susceptible to pest attack (Luna, 1988). Many studies (Scriber, 1984) suggest that the physiological susceptibility of crops to insect pests and pathogens may be affected by the form of fertilizer used (organic versus chemical fertilizer).

The literature is abundant on the benefits of organic amendment additions that encourage resident antagonists thus enhancing biological control of plant diseases (Campbell, 1989). 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 or hyperparasitism (Palti, 1981).

Studies documenting lower abundance of several insect herbivores in low-input systems have partly attributed such reduction to a low N content in organically farmed crops. In Japan, density of immigrants of the planthopper, *Sogatella furcifera*, was significantly lower while settling rate 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 N 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 (*Ostrinia nubilalis*) females preferred to lay significantly more eggs in chemically fertilized plants (Phelan et al., 1995).

In the case of weeds, Liebman and Gallandt (1997) assessed the impacts of organic soil amendments on weed regeneration, resource use and allelopatic interaction. Their results from temperate region sweet corn (*Z. mays*) and potato (*Solanum tuberosum*) producing systems showed that weed species appear to be more susceptible to phytotoxic effects of crop residues and other organic soil amendments that crop species, possibly because of differences in seed mass. They suggest that delayed patterns of N availability in low-external-input systems may favor large-seeded crops over small-seeded weeds. They also found that additions of organic materials can change the incidence and severity of soil-borne diseases affecting weeds but not crops. Such results suggest that these mechanisms ubiquitous to organically managed soils can reduce weed density and growth while maintaining acceptable crop yields.

Such findings are of key importance to resource-poor farmers such as Cakchiquel farmers in Patzúm, Guatemala, who have experienced increased pest populations (aphids and corn earworms (*Heliothis zea*)) in maize since they abandoned organic fertilization and adopted synthetic fertilizers (Morales et al., 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.

6.4. Vegetational diversity and pest outbreaks

Throughout the years many ecologists have conducted experiments testing the theory that decreased plant diversity in agroecosystems leads to enhanced herbivorous insect abundance (Altieri and Letourneau, 1982; Andow, 1991). Many of these experiments 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, 1994).

Several reviews have been published documenting the effects of within-habitat diversity on insects (Altieri and Nicholls, 1999; Landis et al., 2000). 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 (Smith and McSorely, 2000). The literature is full of examples of experiments documenting that diversification of cropping systems often leads to reduced pest populations. In the review by Risch et al. (1983), 150 published studies documenting the effects of agroecosystem diversification on insect pest abundance were summarized; 198 total herbivore species were examined in these studies. 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 Lepidopteran stemborers in Africa. Scientists at the International Center of Insect Physiology and Ecology (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 (the pull) them (Kahn et al., 1998). The push–pull system has been tested on over 450 farms in two districts of Kenya and has now been released for uptake by the national extension systems in East Africa. Participating farmers in the breadbasket of Trans-Nzoia are reporting a 15–20% increase in maize yield. In the semiarid Suba district—plagued by both stemborers and striga—a substantial increase in milk yield has occurred in the last 4 years, with farmers now being able to support grade cows on the fodder produced. When farmers plant maize together with the push–pull plants, 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 in the borers' natural enemies such as the parasitic wasp (*Cotesia sesamiae*), napier grass (*Pennisetum purpureum*) and Sudan grass (*S. 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*), which in addition can suppress the parasitic weed *Striga* by a factor of 40 compared to maize monocrop. *Desmodium's* 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 (Khan et al., 1997).

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 both 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 in such systems can lead to disruptions of natural pest control mechanisms, potentially making farmers more dependent on pesticides.

Regardless, more studies are needed to determine the underlying elements of plant mixtures that disrupt pest invasion and that favor natural enemies. Research must also expand to assess the effects of genetic diversity, achieved through variety mixtures, on the suppression of plant pathogens. In the area of plant disease control, evidence suggests that genetic heterogeneity reduces the vulnerability of monocultured crops to disease. Recent research in China, where four different mixtures of rice varieties grown by farmers from 15 different townships over 3000 ha, suffered 44% less blast incidence and exhibited 89% greater yield than homogeneous fields without the need to use fungicides (Zhu et al., 2000). More studies along these lines will allow more precise planning of cropping designs for optimal pest and disease regulation.

6.5. *Conversion*

In some areas, the challenge is to revert systems that have already undergone modernization and where farmers experience high environmental and economic costs due to reliance on agrochemicals. Such process of conversion from a high-input conventional management system to a low-external-input system can be conceptualized as a transitional process with three marked phases (Mc Rae et al., 1990):

1. Increased efficiency of input use through integrated pest management or integrated soil fertility management.
2. Input substitution or substitution of environmentally benign inputs.
3. System redesign: diversification with an optimal crop/animal assemblage, which encourages syner-

gism so that the agroecosystem may sponsor its own soil fertility, natural pest regulation, and crop productivity.

Many of the practices that are currently being promoted as components of sustainable agriculture fall in categories 1 and 2. Both these stages offer clear benefits in terms of lower environmental impacts as they decrease agrochemical input use and often can provide economic advantages compared to conventional systems. Incremental changes are likely to be more acceptable to farmers as drastic modification that may be viewed as highly risky. But does the adoption of practices that increase the efficiency of input use or that substitute biologically based inputs for agrochemicals, but that leave the monoculture structure intact, really have the potential to lead to the productive redesign of agricultural systems?

In general, the fine-tuning of input use through IPM or ISFM does little to move farmers toward an alternative to high input systems. In most cases, IPM translates to "intelligent pesticide management" as it results in selective use of pesticides according to a pre-determined economic threshold, which pests often "surpass" in monoculture situations.

On the other hand, input substitution follows the same paradigm of conventional farming; overcoming the limiting factor but this time with biological or organic inputs. Many of these "alternative inputs" have become commodified, therefore farmers continue to be dependent on input suppliers, many of a corporate nature (Altieri and Rosset, 1996). Clearly, as it stands today, "input substitution" has lost its "pro-poor" potential. A notable exception are advances in Cuba, where small-scale artisanal production of biopesticides and biofertilizers is conducted in cooperatives using local materials and made available to farmers at low costs.

System redesign on the contrary arises from the transformation of agroecosystem function and structure by promoting management guided to ensure the following processes:

1. increasing above- and below-ground biodiversity,
2. increasing biomass production and soil organic matter content,
3. optimal planning of plant–animal sequences and combinations and efficient use of locally available resources, and
4. enhancement of functional complementarities between the various farm components.

Promotion of biodiversity within agricultural systems is the cornerstone strategy of system redesign, as research has demonstrated that (Power, 1999):

1. Higher diversity (genetic, taxonomic, structural, resource) within the cropping system leads to higher diversity in associated biota.
2. Increased biodiversity leads to more effective pest control and pollination.
3. Increased biodiversity leads to tighter nutrient cycling.

As more information about specific relationships between biodiversity, ecosystem processes, and productivity in a variety of agricultural systems is accumulated, design guidelines can be developed further and used to improve agroecosystem sustainability and resource conservation.

6.6. *Syndromes of production*

One of the frustrations of research in sustainable agriculture has been the inability of low-input practices to outperform conventional practices in side-by-side experimental comparisons, despite the success of many organic and low-input production systems in practice (Vandermeer, 1997). A potential explanation for this paradox was offered by Andow and Hidaka (1989) in their description of "syndromes of production". These researchers compared the traditional shizeñ system of rice (*Oryza sativa*) production with the contemporary Japanese high input system. Although rice yields were comparable in the two systems, management practices differed in almost every respect: irrigation practice, transplanting technique, plant density, fertility source and quantity, and management of insects, diseases, and weeds. Andow and Hidaka (1989) argue that systems like shizeñ function in a qualitatively different way than conventional systems. This array of cultural technologies and pest management practices result in functional differences that cannot be accounted for by any single practice.

Thus a production syndrome is a set of management practices that are mutually adaptive and lead to high performance. However, subsets of this collection of practices may be substantially less adaptive, i.e. the interaction among practices leads to improved system performance that cannot be explained by the additive effects of individual practices. In other words, each production system represents a distinct group of management techniques and by implication, ecological relations. This re-emphasizes the fact that agroecological designs are site-specific and what may be applicable elsewhere are not the techniques but rather the ecological principles that underlie sustainability. It is of no use to transfer technologies from one site to another, if the set of ecological interactions associated with such techniques cannot be replicated.

6.7. *Assessing the sustainability of agroecosystems*

How can the sustainability of an agroecosystem be evaluated? How does a given strategy impact on the overall sustainability of the natural resource management system? What is the appropriate approach to explore its economic, environmental and social dimensions? These are unavoidable questions faced by scientists and development practitioners dealing with complex agroecosystems. A number of people working on alternative agroecological strategies have attempted to arrive at a framework that offers a response to the above and other questions (Conway, 1994). There is much argument on whether to use location-specific or universal indicators. Some argue that the important indicators of sustainability are location-specific and change with the situation prevailing on a farm (Harrington, 1992). For example, in the steeplands, soil erosion has a major impact on sustainability, but in the flat lowland rice paddies, soil loss due to erosion is insignificant and may not be a useful indicator. Based on this principle, therefore, the protocol for measuring sustainability starts with a list of potential indicators from which practitioners select a subset of indicators that is felt to be appropriate for the particular farm being evaluated.

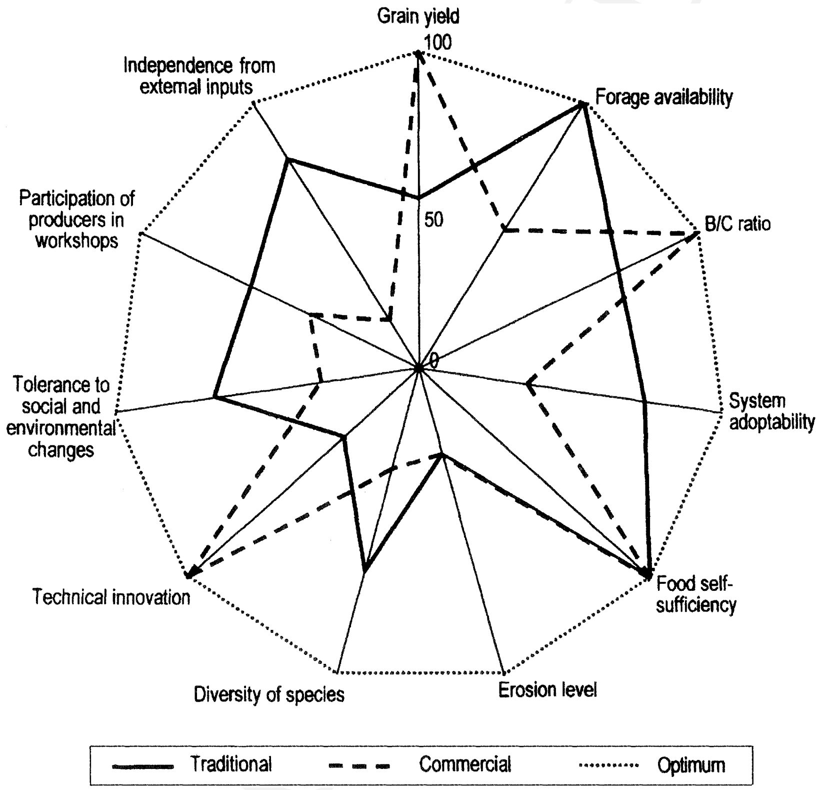


Fig. 3. An AMOEBA-type diagram featuring 11 indicators for the evaluation of the sustainability of two contrasting agrosilvopastoral systems in Casa Blanca, Michoacan, Mexico (Lopez-Ridaura et al., 2000).

A strong current of opinion thinks that the definition and consequently the procedure for measuring sustainable agriculture is the same regardless of the diversity of situations that prevails on different farms. Under this principle, sustainability is defined by a set of requirements that must be met by any farm regardless of the wide differences in the prevailing situation (Harrington, 1992). The procedure of using a common set of indicators offers a protocol for measuring sustainability at the farm level by: (i) defining the requirements for sustainability, (ii) selecting the common set of indicators, (iii) specifying the threshold levels, (iv) transforming the indicators into a sustainability index, and (v) testing the procedure using a set of data from selected farms (Gomez et al., 1996). According to this method, a farming system is considered sustainable if it conserves the natural resource base and continues to satisfy the needs of the farmer, the manager of the system. Any system that fails to satisfy these two requirements is bound to change significantly over the short term and is therefore considered not sustainable. Using threshold levels (minimum value of an indicator above which starts a trend towards sustainability), Gomez et al. (1996) used yields, profit and stability (frequency of disaster) as farmers satisfaction indicators, while soil depth, water holding capacity, nutrient balance, organic matter content, ground cover, and biological diversity were used as indicators of resource conservation.

In contrast, by working with optimal values (rather than with thresholds) of sustainability, Lopez-Ridaura et al. (2000) used indicators such as independence from external inputs, grain yield, system adoptability, food self-sufficiency, diversity of species, etc. As shown in Fig. 3, an AMOEBA-type diagram is used to show, in qualitative terms, how far the objective has been reached for each indicator by giving the percentage of the actual value with respect to the ideal value (reference value). This enables a simple, yet comprehensive comparison of the advantages and limitations of two systems being evaluated and compared.

7. Applying agroecology to improve the productivity of small farming systems

Since the early 1980s, hundreds of agroecologically based projects have been promoted by NGOs throughout the developing world, which incorporate elements of both traditional knowledge and modern agricultural science. A variety of projects exist featuring resource-conserving yet highly productive systems such as polycultures, agroforestry, the integration of crops and livestock, etc. (Altieri et al., 1998). Such alternative approaches can be described as low-input technologies, but this designation refers to the external inputs required. The amount of labor, skills and management that are required as inputs to make land and other factors of production most productive is quite substantial. So rather than focus on what is not being utilized, it is better to focus on what is most important to increase food output, labor, knowledge and management (Uphoff and Altieri, 1999).

Agroecological alternative approaches are based on using locally available resources as much as possible, though they do not totally reject the use of external inputs. However, farmers cannot benefit from technologies that are not available, affordable or appropriate to their conditions. Purchased inputs present special problems and risks for less-secure farmers, particularly where supplies and the credit to facilitate purchases are inadequate.

The analysis of dozens of NGO-led agroecological projects show convincingly that agroecological systems are not limited to producing low outputs, as some critics have asserted. Increases in production of 50–100% are fairly common with most alternative production methods. In some of these systems, yields for crops that the poor rely on most—rice (*O. sativa*), beans (*Phaseolus vulgaris*), maize, cassava (*Manihot esculenta*), potatoes (*M. esculenta*), barley—have been increased by several-fold, relying on labor and know-how more than on expensive purchased inputs, and capitalizing on processes of intensification and synergy (Uphoff, 2002).

In a recent study of 208 agroecologically based projects and/or initiatives throughout the developing world, Pretty and Hine (2000) documented clear increases in food production over some 29 million ha, with nearly nine million households benefiting from increased food diversity and security. Promoted sustainable agriculture practices led to 50–100% increases in per hectare food production (about 1.71 Mg per year per household) in rain-fed areas typical of small farmers living in marginal environments, i.e. an area of about 3.58 million ha, cultivated by about 4.42

million farmers. Such yield enhancements are a true breakthrough for achieving food security among farmers isolated from mainstream agricultural institutions.

More important than just yields, agroecological interventions raise total production significantly through diversification of farming systems, such as raising fish in rice paddies or growing crops with trees, or adding goats or poultry to household operations (Uphoff and Altieri, 1999). Agroecological approaches increased the stability of production as seen in lower coefficients of variance in crop yield with better soil and water management (Francis, 1988).

It is difficult, however, to quantify all the potentials of such diversified and intensified systems because there is too little research and experience to establish their limits. Nevertheless, data from agroecological field projects show that traditional crop and animal combinations can often be adapted to increase productivity when the biological structuring of the farm is improved and labor and local resources are efficiently used (Altieri, 1999). In general, data show that over time agroecological systems exhibit more stable levels of total production per unit area than high-input systems, produce economically favorable rates of return, provide a return to labor and other inputs sufficient for a livelihood acceptable to small farmers and their families, and ensure soil protection and conservation as well as enhanced biodiversity (Pretty, 1997).

8. Current limitations to the widespread use of agroecology

With increasing evidence and awareness of the advantages of agroecology, why has not it spread more rapidly and how can it be multiplied and adopted more widely? A key obstacle to the use of agroecology is the demand for specificity in its application. Contrary to conventional systems featuring homogeneous technological packages designed for ease of adoption and that lead to agroecosystem simplification, agroecological systems require that principles are applied creatively within each particular agroecosystem. Field practitioners must have more diversified information on ecology and on agricultural and social sciences in general. Today's agronomy curricula, focused on applying the "Green Revolution" technological kit, is simply unfit to deal with the complex realities facing small farmers (Pearse, 1980). This situation is changing, although slowly, as many agricultural universities have started to incorporate agroecology and sustainability issues into the conventional agronomic curriculum (Altieri and Francis, 1992).

The high variability of ecological processes and their interactions with heterogeneous social, cultural, political, and economic factors generate local systems that are exceptionally unique. When the heterogeneity of the rural poor is considered, the inappropriateness of technological recipes or blueprints becomes obvious. The only way that the specificity of local systems—from regions to watersheds and all the way down to a farmer's field—can be taken into account is through site-specific NRM (Beets, 1990). This does not mean, however, that agroecological schemes adapted to specific conditions may not be applicable at ecologically and socially homologous larger scales. What implies is the need to understand the principles that explain why such schemes work at the local level, and later applying such principles at broader scales.

NRM site-specificity requires an exceptionally large body of knowledge that no single research institution can generate and manage on its own. This is one reason why the inclusion of local communities at all stages of projects (design, experimentation, technology development, evaluation, dissemination, etc.) is a key element in successful rural development. The inventive self-reliance of rural populations is a resource that must be urgently and effectively mobilized (Richards, 1985).

On the other hand, technological or ecological intentions are not enough to disseminate agroecology. As pointed out in Table 5, there are many factors that constraint the implementation of sustainable agriculture initiatives. Major changes must be made in policies, institutions, and research and development agendas to make sure that agroecological alternatives are adopted, made equitably and broadly accessible, and multiplied so that their full benefit for sustainable food security can be realized. It must be recognized that a major constraint to the spread of agroecology has been that powerful economic and institutional interests have backed research and development for the conventional agroindustrial approach, while research and development for agroecology and sustainable approaches has been largely ignored or even ostracized. Only in recent

Table 5
Key constrains to implementing sustainable agriculture partnerships (modified from Thrupp, 1996)

- Macroeconomic policies and institutions
  - Pesticides incentives and subsidies
  - Export orientation and monocultural focus of conventional policies
  - Lack of incentives for institutional partnerships
- Pressures from agrochemical companies
  - Political and economic power wielded against IPM
  - Advertising and sales practices
- Funding/donor issues and sustainability questions
  - Lack of funding, especially long-term support
  - Lack of recognition of IPM/sustainable agriculture benefits
  - Need for reducing dependency on donors and for developing local support
- Lack of information and outreach on innovative alternative methods
- Weak internal capacities of institutions involved
  - Institutional rigidities among some collaborators
  - Lack of experience with agroecology and participatory methods
  - Social and health concerns sometimes neglected
  - Lack of communication and cooperation skills (among some groups)

years has there been growing realization of the advantages of alternative agricultural technologies (Pretty, 1995).

The evidence shows that sustainable agricultural systems can be both economically, environmentally and socially viable, and contribute positively to local livelihoods (Uphoff and Altieri, 1999). But without appropriate policy support, they are likely to remain localized in extent. Therefore, a major challenge for the future entails promoting institutional and policy changes to realize the potential of the alternative approaches. Necessary changes include:

- Increasing public investments in agroecological—participatory methods.
- Changes in policies to stop subsidies of conventional technologies and to provide support for agroecological approaches.
- Improvement of infrastructure for poor and marginal areas.
- Appropriate equitable market opportunities including fair market access and market information to small farmers.
- Security of tenure and progressive decentralization processes.
- Change in attitudes and philosophy among decision-makers, scientists, and others to acknowledge and promote alternatives.
- Strategies of institutions encouraging equitable partnerships with local NGOs and farmers; replace top-down transfer of technology model with participatory technology development and farmer centered research and extension.

9. Scaling up of agroecological innovations

Throughout Africa, Asia and Latin America there are many NGOs involved in promoting agroecological initiatives that have demonstrated a positive impact on the livelihoods of small farming communities in various countries (Pretty, 1995). Success is dependent on the use of a variety of agroecological improvements that in addition to farm diversification favoring a better use of local resources, also emphasize human capital enhancement and community empowerment through training and participatory methods as well as higher access to markets, credit and income generating activities (Fig. 4). Pretty and Hine’s (2001) analysis point at the following factors as underlying the success of agroecological improvements:

- Appropriate technology adapted by farmers’ experimentation;
- Social learning and participatory approaches;
- Good linkages between farmers and external agencies, together with the existence of working partnerships between agencies;
- Presence of social capital at local level.

In most cases, farmers adopting agroecological models achieved significant levels of food security and natural resource conservation. Given the benefits and advantages of such initiatives, two basic questions emerge: (1) why these benefits have not disseminated more widely and (2) how to scale-up these initiatives to enable wider impact? For the purposes of this paper, scaling up is defined as the dissemination and adoption of agroecological principles over substantial areas by large numbers of farmers and technical staff. In other words, scaling up means achieving a significant increase in the knowledge and management of agroecological principles and technologies between farmers of varied socioeconomic and biophysical

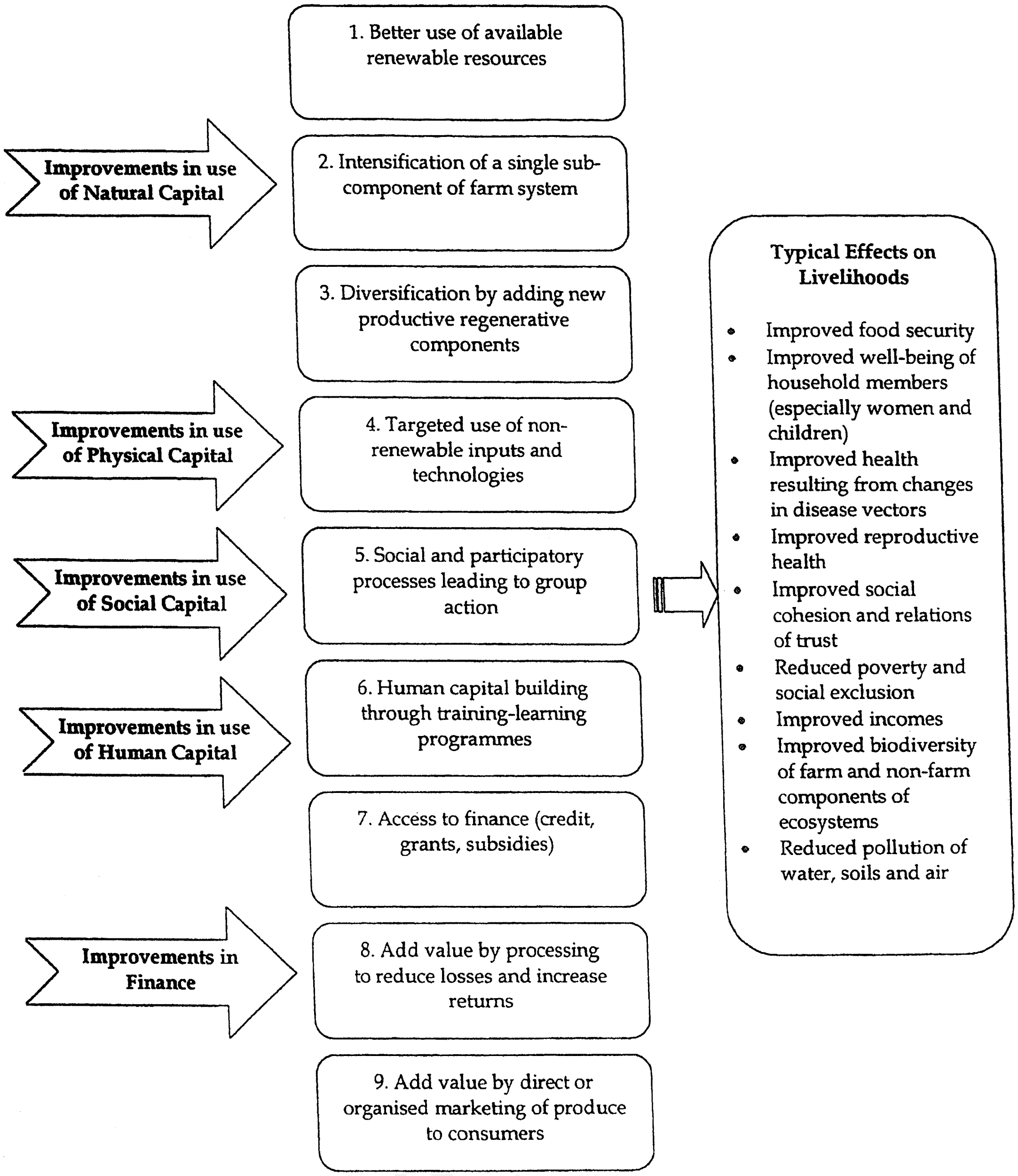
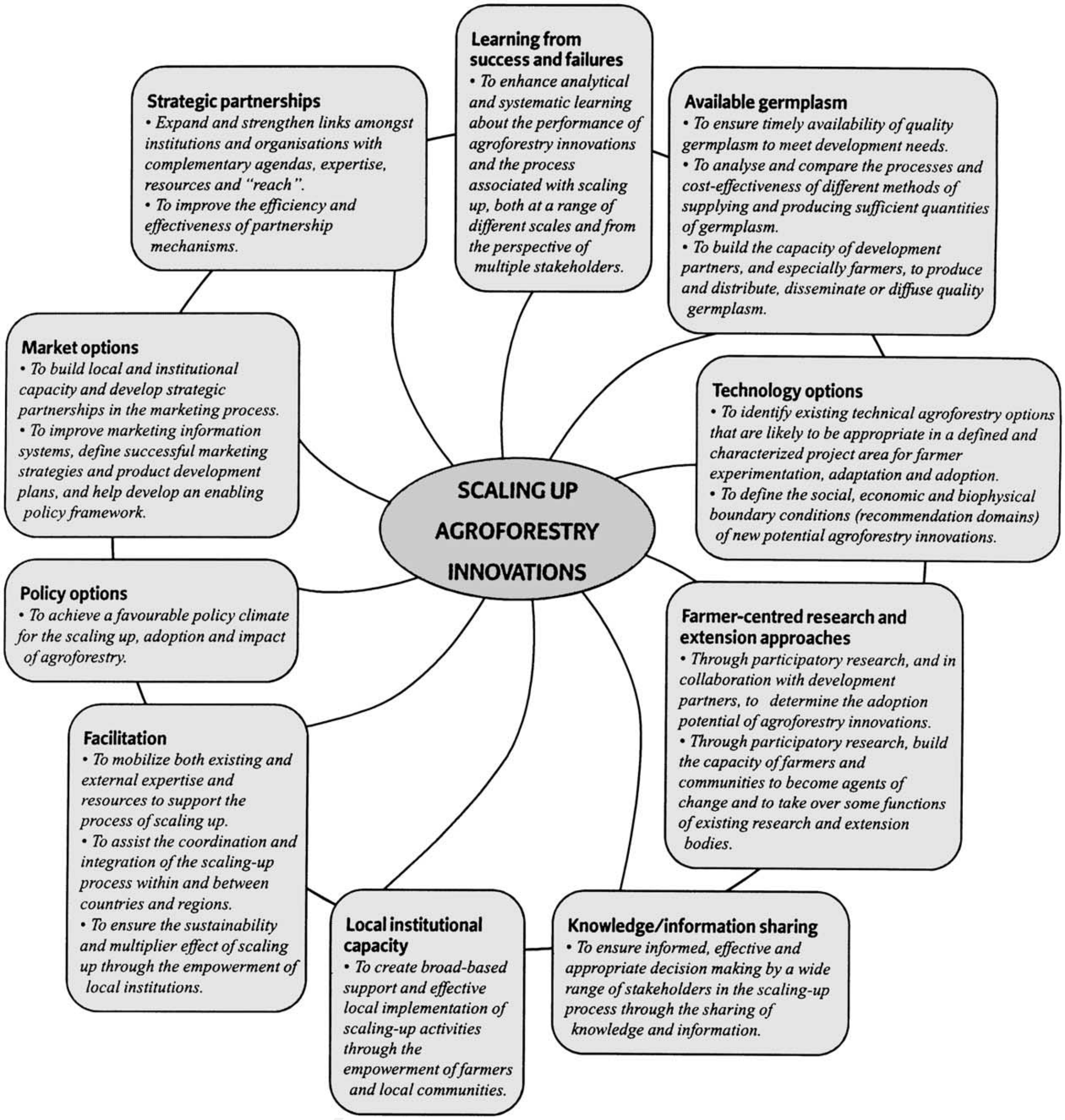


Fig. 4. Entry points for sustainable agriculture improvements leading to more sustainable livelihoods (Pretty and Hine, 2000).

conditions, and between institutional actors involved in peasant agricultural development.

One important factor limiting the spread of agroecological innovations is that for the most part NGOs promoting such initiatives have not analyzed or systematized the principles that determined the level of success of the local initiatives, nor have been able to validate specific strategies for the scaling-up of such initiatives. A starting point therefore should be the understanding of the agroecological and socioeconomic conditions under which alternatives were adopted and implemented at the local level. Such information can shed light on the constraints and opportunities farmers to whom benefits should be expanded at a more regional level are likely to face.

An unexplored approach is to provide additional methodological or technical ingredients to existing cases that have reached a certain level of success. Clearly, in each country there are restraining factors such as lack of markets, and lack of appropriate



Learning from success and failures
- *To enhance analytical and systematic learning about the performance of agroforestry innovations and the process associated with scaling up, both at a range of different scales and from the perspective of multiple stakeholders.*

Strategic partnerships
- *Expand and strengthen links amongst institutions and organisations with complementary agendas, expertise, resources and "reach".*
- *To improve the efficiency and effectiveness of partnership mechanisms.*

Available germplasm
- *To ensure timely availability of quality germplasm to meet development needs.*
- *To analyse and compare the processes and cost-effectiveness of different methods of supplying and producing sufficient quantities of germplasm.*
- *To build the capacity of development partners, and especially farmers, to produce and distribute, disseminate or diffuse quality germplasm.*

Market options
- *To build local and institutional capacity and develop strategic partnerships in the marketing process.*
- *To improve marketing information systems, define successful marketing strategies and product development plans, and help develop an enabling policy framework.*

Technology options
- *To identify existing technical agroforestry options that are likely to be appropriate in a defined and characterized project area for farmer experimentation, adaptation and adoption.*
- *To define the social, economic and biophysical boundary conditions (recommendation domains) of new potential agroforestry innovations.*

Policy options
- *To achieve a favourable policy climate for the scaling up, adoption and impact of agroforestry.*

Farmer-centred research and extension approaches
- *Through participatory research, and in collaboration with development partners, to determine the adoption potential of agroforestry innovations.*
- *Through participatory research, build the capacity of farmers and communities to become agents of change and to take over some functions of existing research and extension bodies.*

Facilitation
- *To mobilize both existing and external expertise and resources to support the process of scaling up.*
- *To assist the coordination and integration of the scaling-up process within and between countries and regions.*
- *To ensure the sustainability and multiplier effect of scaling up through the empowerment of local institutions.*

Local institutional capacity
- *To create broad-based support and effective local implementation of scaling-up activities through the empowerment of farmers and local communities.*

Knowledge/information sharing
- *To ensure informed, effective and appropriate decision making by a wide range of stakeholders in the scaling-up process through the sharing of knowledge and information.*

Fig. 5. Key requirements and components for the scaling-up of agroecological innovations (Cooper and Denning, 2001).

agricultural policies and technologies which limit scaling up. On the other hand, opportunities for scaling-up exist, including the systematization and application of approaches that have met with success at local levels, and the removal of constraining factors (IIRR, 2000). Thus scaling-up strategies must capitalize on mechanisms conducive to the spread of knowledge and techniques, such as:

- Strengthening of producers' organizations through alternative marketing channels. The main idea is to evaluate whether the promotion of alternative farmer-led markets constitute a mechanism to enhance the economic viability of the agroecological approach and thus provide the basis for the scaling-up process.
- Develop methods for rescuing/collecting/evaluating promising agreocological technologies generated by experimenting farmers and making them known to other farmers for wide adoption in various areas. Mechanisms to disseminate technologies with high potential may involve farmer exchange visits, regional–national farmer conferences, and publication of manuals that explain the technologies for the use by technicians involved in agroecological development programs.
- Training government research and extension agencies on agroecology in order for these organizations to include agroecological principles in their extension programs.
- Develop working linkages between NGOs and farmers organizations. Such alliance between technicians and farmers is critical for the dissemination of successful agroecological production systems emphasizing biodiversity management and rational use of natural resources.

Cooper and Denning (2001) provide 10 fundamental conditions and processes that should be considered when scaling-up agroforestry innovations. More effective farmers organizations, research-extension institutional partnerships; exchanges, training, technology transfer and validation in the context of farmer to farmer activities, enhanced participation of small farmers in niche markets, etc. are all important requirements (Fig. 5). From their worldwide survey of sustainable agriculture initiatives, Pretty and Hine (2001) concluded that if sustainable agriculture is to spread to larger numbers of farmers and communities, then future attention needs to be focused on:

1. Ensuring the policy environment is enabling rather than disabling;
2. Investing in infrastructure for markets, transport and communications;
3. Ensuring the support of government agencies, in particular, for local sustainable agricultural initiatives;
4. Developing social capital within rural communities and between external agencies.

The main expectation of a scaling-up process is that it should expand the geographical coverage of participating institutions and their target agroecological projects while allowing an evaluation of the impact of the strategies employed. A key research goal should be that the methodology used will allow for a comparative analysis of the experiences learned, extracting principles that can be applied in the scaling-up of other existing local initiatives, thus illuminating other development processes.

10. Outlook and prospects

There is no question that small farmers located in marginal environments in the developing world can produce much of their needed food (Uphoff and Altieri, 1999; Pretty and Hine, 2000). The evidence is conclusive: new approaches and technologies spearheaded by farmers, NGOs and some local governments around the world are already making a sufficient contribution to food security at the household, national and regional levels. A variety of agroecological and participatory approaches in many countries show very positive outcomes even under adverse conditions. Potentials include: raising cereal yields from 50 to 200%, increasing stability of production through diversification, improving diets and income, contributing to national food security and even to exports and conservation of the natural resource base and agrobiodiversity (Pretty, 1995; Uphoff and Altieri, 1999).

Whether the potential and spread of these thousands of local agroecological innovations is realized depends on several factors and actions. First, proposed NRM strategies have to deliberately target the poor, and not only aim at increasing production and conserving natural resources, but also create employment, provide

Table 6
Elements and contributions of an appropriate NRM strategy

Contribute to greater environmental preservation	Promotion of resource-conserving multifunctional technologies
Enhance production and household food security	Participatory approaches for community involvement and empowerment
Provide on- and off-farm employment	Institutional partnerships
Provision of local inputs and marketing opportunities	Effective and supportive policies

access to local inputs and output markets (Table 6). New strategies must focus on the facilitation of farmer learning to become experts on NRM and at capturing the opportunities in their diverse environments (Uphoff, 2002).

Second, researchers and rural development practitioners will need to translate general ecological principles and natural resource management concepts into practical advice directly relevant to the needs and circumstances of smallholders. The new pro-poor technological agenda must incorporate agroecological perspectives. A focus on resource conserving technologies, that uses labor efficiently, and on diversified farming systems based on natural ecosystem processes will be essential. This implies a clear understanding of the relationship between biodiversity and agroecosystem function and identifying management practices and designs that will enhance the right kind of biodiversity which in turn will contribute to the maintenance and productivity of agroecosystems.

Technological solutions will be location-specific and information-intensive rather than capital-intensive. The many existing examples of traditional and NGO-led methods of natural resource management provide opportunities to explore the potential of combining local farmer knowledge and skills with those of external agents to develop and/or adapt appropriate farming techniques.

Any serious attempt at developing sustainable agricultural technologies must bring to bear local knowledge and skills on the research process (Richards, 1995; Toledo, 2000). Particular emphasis must be given to involving farmers directly in the formulation of the research agenda and on their active participation in the process of technological innovation and dissemination. The focus should be in strengthening local research and problem-solving capacities. Organizing local people around NRM projects that make effective use of traditional skills and knowledge provides a launching pad for additional learning and organizing, thus improving prospects for community empowerment and self-reliant development.

Third, major changes must be made in policies, institutions, and research and development to make sure that agroecological alternatives are adopted, made equitably and broadly accessible, and multiplied so that their full benefit for sustainable food security can be realized. Existing subsidies and policy incentives for conventional chemical approaches must be dismantled. Corporate control over the food system must also be challenged. The strengthening of local institutional capacity and widening access of farmers to support services that facilitate use of technologies will be critical Governments and international public organizations must encourage and support effective partnerships between NGOs, local universities, and farmer organizations in order to assist and empower poor farmers to achieve food security, income generation, and natural resource conservation.

There is also need to increase rural incomes through interventions other than enhancing yields such as complementary marketing and processing activities. Therefore equitable market opportunities should also be developed, emphasizing fair trade and other mechanisms that link farmers and consumers more directly. The ultimate challenge is to increase investment and research in agroecology and scale-up projects that have already proven successful to thousands of other farmers. This will generate a meaningful impact on the income, food security and environmental well-being of the world's population, especially of the millions of poor farmers yet untouched by modern agricultural technology.

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