

Review article

Global change and multi-species agroecosystems: Concepts and issues

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Abstract

Complex (multi-species) agroecosystems change rapidly as a result of farmers' decisions based on their perception of opportunities and constraints. Overall, the major trend is still one of reducing complexity. This review addresses the driving forces as well as consequences of this change and discusses the hypothesis that complex agricultural systems are more dependable in production and more sustainable in terms of resource conservation than simple ones. Farmer decisions regarding planned diversity on the farm have consequences not only for the harvested produce, but also for associated diversity and non-harvested components which may contribute to ecological sustainability. Functional attributes of plants which can lead to complementarity in resource capture include root architecture and phenology. Three hypotheses on biodiversity and ecosystem function are formulated (ranging from weak negative to strong positive interactions) and discussed. Evidence is not yet conclusive. © 1998 Elsevier Science B.V.

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1. Introduction

Recent concern with agricultural responses to global change have concentrated on specific crops and their likely increase or decrease in production (Parry, 1990). Most of this literature concentrates on expected climate changes resulting from elevated CO₂ and other greenhouse gases. Although such concern is legitimate, the majority of the world's

farmers, particularly those located in the tropical regions, depend for their food and income on multi-species agriculture—the cultivation of a variety of crops and/or livestock on a single piece of land, located on a farm that usually contains diverse habitats, in the context of a complex landscape of diverse productive and non-productive units. What might be the consequences of projected global changes on this sector?

Small-scale farming, especially in tropical regions, undoubtedly faces problems that are distinct from those faced by large-scale industrial farming, and the expected consequences of global changes are

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thus likely to be different. Yet these systems are less researched and more complex to model than monocultures. Their behavior and productivity under global change is, therefore, less easy to predict. Furthermore, the social and economic circumstances under which multi-species farming systems are managed is in most cases quite different from the 'agribusiness' context of intensive monocultures (Goodman et al., 1987). For most farming communities dependent on multi-species agriculture, the whole family livelihood and culture are embedded in the farming practice and its environment. There are consequently a wide range of factors to consider in any evaluation of global change affecting this sector (Parry, 1990; Swift et al., 1996).

Global change in agroecosystems is largely the result of decisions of a multitude of individual farmers to the options and constraints they perceive. Expectations and real effects of climatic change and changed composition of the atmosphere may play a role in these farmer decisions, but should be seen in a broader context. Agroecosystems are continuously changing as farmers respond to new opportunities and constraints.

Complex (multi-species) agroecosystems are here defined as farming landscapes which involve more than a combination of fields with large-scale monocultures, be they annual crops or plantations of tree crops. They still represent the majority of land use

systems in the tropics. Complexity is a multi-scale attribute of such systems, which tend to integrate rather than segregate components contributing to multiple objectives. Yet, the major part of research and development efforts has been, and remains, aimed at accelerating the transition of these complex systems into simpler ones based on monocultures of intensively managed food crops or monocultural plantations of tree crops (such as oil palm or rubber) (Goodman et al., 1987; Deo and Swanson, 1990). The drive to further segregation of functions via simplification and specialization of agroecosystems under the pressure of economic development may in part, be a fully rational and inevitable process. It may, however, also be partly the effect of incomplete evaluation of the more complex and integrated alternatives (Tomich et al., 1998).

Land use systems serve different functions to different groups of people. These functions include the production of staple foods and tree products, the conservation of soil, water and biodiversity and the mitigation of greenhouse gas emissions. Advocates of agroforestry and 'integrated' land use generally have optimistic views on how well these different functions can be combined. A central research question is which functions can be combined and which ones are better served separately. In theory, at least, there is always a choice between simple (one function at a time—segregated) and more complex (com-

Table 1
'Integration' and 'segregation' as options in land use at a range of scales and for a range of functions

Functions	Segregated option	Integrated option
Production of various plant products	A combination of annuals and trees, each for a different product	'Multipurpose' trees or crops
Production of tree and crop products	Separate crop fields and woodlots; sequential agroforestry systems	Simultaneous tree-crop agroforestry systems
Soil and water conservation and agricultural production	Erosion in 'alleys' and sediment traps in 'contour strips'; erosion on slopes, filter strips along rivers, rice fields in valleys	Continuous mulch cover
Productivity and risk reduction Biodiversity conservation and agricultural production	Specialized farms with insurance schemes National parks and separate zones for intensive agriculture	Mixed farms (crop-animal-tree) Agroforests, multifunctional forests
Agricultural production and mitigation of greenhouse gas emissions	Sinks (e.g., forest soils as sink) make up for sources elsewhere (e.g., rice fields as source)	Crop and soil management to reduce on-site emissions
Food security and economic growth	'Economic efficiency' strategies; specialization; reliance on markets	'Self reliance' strategies at national scale

bined functions—integrated) land use systems (Table 1). Table 1 illustrates how the ‘segregate–integrate’ choice may apply at different scales in the landscape and for different combinations of functions. The ‘integrated’ option should in each case be compared with its relevant ‘segregated’ option. A change from an ‘integrated’ to a ‘segregated’ option does not in itself reduce overall diversity, but it will reduce the intensity of interactions and trade-offs and thus most likely reduce ‘complexity.’

Beginning with the highly diverse farms of true subsistence economies, a dominant trend in modern agriculture has been simplification and specialization. Such specialization is based on the externalization of functions of farm components, including: (a) a range of subsistence products: market supply replaces production of all household goods; (b) seed stock: traditional varieties replaced by modern, frequently hybrid, cultivars; (c) pest control: chemical solutions replace local ecological ones; (d) soil fertility maintenance: chemical fertilizer inputs replace local ‘service’ components; (e) animal feed: market supply replaces local production of fodder; (f) labor: mechanization replaces human labor, both family

and hired; (g) insurance: social and market-based insurance schemes replace stabilizing effect of farm diversity; (h) institutional factors: land tenure can be claimed by other means than trees and other natural features as markers.

The benefits of specialization are based on ‘economies of scale’ where mechanization, specialized know-how and marketing are involved and on exploiting comparative advantages of the local production situation (Table 2). The resulting simplification has a pronounced effect on field and farm-level diversity, but not necessarily on regional and national level diversity. It is first of all a change in ‘grain size’, a shift in the ‘segregate–integrate’ continuum.

Although this trend to specialization is a marked aspect of ‘development’, it has clear drawbacks as well as direct financial benefits. Aspects of global change may increase the drawbacks: (a) increased uncertainty of local climate may increase the need for ‘insurance’; (b) pest outbreaks and weed invasion may increase in response to modified climate and increased climate variability; (c) environmental side-effects of chemical inputs and the energy needed

Table 2
Proposed driving forces for reducing and enhancing complexity of agroecosystems

Reducing	Enhancing
Increased awareness and reduced tolerance of competition for resources among components	Recognition and selection of plant–plant combinations which exhibit true complementary in resource use and may thus have real agronomic advantages
Mechanization, which restricts the opportunities for planned mixed cropping, especially at the transition from manual field operations to draught-animal traction, with further reductions at the transition from animal to tractor-based systems	Appropriate technology’ developments in mechanization which allow higher labor use efficiencies without a strong drive for simplifying field plant combinations
Intensification of land use, aiming for higher economic outputs per hectare, reducing the thresholds for ‘weediness’	Extensification of land use, as occurs in later stages of economic transformations of (formerly) agricultural economies, when returns to labor are higher in other sectors of the economy
Market integration of the farm household, inducing specialization and its ensuing segregation	Effective rewards from society at large in niche markets or by effective policies for maintaining complexity in as far as it is valuable to interest groups beyond the farm
The use of ‘hybrid’ germplasm which is not conducive to local selection and depends on a continuous external source of ‘quality seeds’	On-farm selection of germplasm and the continuous introduction of new germplasm, maintaining or enhancing the ‘transient diversity’ aspect of the farms
Extension services and ‘projects’ which tend to reduce between-actor variation, especially in combination with ‘planning’ and ‘models’ in the sense of ‘blue-prints’- usually enforced, if not by social pressure by credit schemes leaving few options.	Development of models which allow more location-specificity in development options, adjusting credit schemes to the real qualities of the site and real objectives of the farmer instead of ‘blue prints’.

to produce them are less tolerated by society; (d) loss of environmental service functions (regulation of stream and sediment flows, biodiversity conservation) may lead to increasing conflicts with downstream land users.

Although simplified systems may indeed be superior from a farmer's perspective, it is also possible that a bias is introduced by agricultural research which has an adequate tool-box of experiments and models for technology development in monocultures, but which is less able to deal with more complex systems. Perhaps specific forms of more complex systems would indeed be better for farmers and/or local communities, but the knowledge base for evaluating this possibility is incomplete. This represents a challenge to research to reappraise the significance of current complexity and then develop a tool-box for technology development that will maintain and enhance those aspects of complexity deemed valuable. An analysis is also needed of the role markets and policies play in the current process of change, to evaluate together with policy makers where long term values are compromised (e.g., market and policy failures).

Although the risks attendant to 'over specialization' under current conditions are clear, the dangers may increase yet further under global change. However, the current socioeconomic situation continues to generate a major drive towards simplification. Going against this tendency will involve a variety of costs and certainly a loss of short term profitability. How strong are the arguments for maintaining complexity? How well can we distinguish situations where it is essential? What sorts of interventions may be needed to reverse the trend to simplification? Will the threat of global change cause agroecosystem complexity to take on a different significance in policy debate?

Despite the comparatively small intensity of research aimed at these sorts of questions (Vandermeer and Perfecto, 1997), current concerns with the sustainability of agricultural practices have led to increased interest in them as a means of stabilizing food production and conserving natural resources and environments, particularly in the tropics (Altieri, 1983, 1991c, 1995; Richards, 1985; Swift et al., 1996; Gliessman et al., 1981; Paoletti and Pimentel, 1992). The accelerating rate of global change in

climate, land degradation, and atmospheric composition simply adds a new dimension to this goal, as argued above. As a tentative hypothesis, the authors propose that under conditions of global change, complex agricultural systems are more dependable in production and more sustainable in terms of resource conservation than simple ones (Swift and Ingram, 1996).

Global change includes land-use change as well as atmospheric changes. Given that all such changes are potentially serious, the one with the most immediate effect on agriculture is land-use change. This includes both abrupt and major changes such as the switch from natural vegetation to cultivation or of farming to plantation, and the more incremental changes associated with what is often termed 'agricultural intensification' (Swift et al., 1996; Perfecto et al., 1997). The notion of agricultural intensification is a qualitative idea intended to provide a conceptual framework for thinking about changes in multi-species agriculture. Farmers modify farming practices in response to a wide range of physical, demographic, economic, social and technological pressures. These modifications may be expressed in relation to agricultural intensification, the most fundamental feature of which is increasing the duration for which the same piece of land is used. Associated aspects of intensification include increased use of resources, the switch from internal to external regulation through the use of purchased inputs, changes in labor use and management practice, and increased linkage with market economies. Another, almost universal, feature of agricultural intensification is that of increasing specialization in the production process, resulting in reduction in the number of crop and/or livestock species utilized and an apparent reduction in other, unplanned, components of biodiversity (Perfecto et al., 1997; Giller et al., 1997).

The overarching imperative of such changes is the search for increased land or labor productivity. The perceived benefits of moving down a path of specialization as opposed to diversification are gains in productivity through improved efficiency in production. In this model, specialization implies (inter alia) optimizing the system through reducing plant competition, maximizing access to resources for the target productive plant, optimizing harvest index and reducing physiological redundancy. Beyond the plant-

scale, there are other perceived benefits in the use of labor through management task specialization and mechanization. Beyond the farm, there are economies to be gained at the level of more specialized organization in the market system (Tomich et al., 1995).

The switch from complex agricultural systems (using a multiplicity of productive species) to less complex systems with lower species numbers (the ultimate extreme of which is monoculture) has been a major feature of agricultural development in the last 50 yr (but see Netting and Stone (1996) for an interesting exception). This switch has been largely driven by market forces, the practice of monoculture being perceived as economically more efficient than more complex practices. Questions have been raised, however, as to whether the loss of complexity also results in increased economic and ecological instability (Clawson, 1985). Recent concerns with sustainability as well as global change have brought these issues to the fore and reawakened interest in production systems of ‘intermediate’ diversity and complexity, such as intercrops and agroforestry systems (Vandermeer, 1989; Francis, 1986; Huxley, 1983).

Multi-species cultivation clearly necessitates biodiversity management at the plot-scale. It also, however, requires consideration of its biogeographical context within the surrounding area, requiring recognition of processes operating at various scales. In addition to scalar differences, the system biodiversity itself (and therefore its functional importance), can be split into two categories, planned and associated (Perfecto et al., 1997; Swift et al., 1996). The former includes the plants and livestock deliberately incorporated into the system by the farmer. The latter includes the other biota, above- and below-ground, which influence the productivity of the site. These, which are often not readily identifiable, include weeds and beneficial plants serving non-yield related functions, above-ground pests and associated predators (which may have refugia in surrounding areas), the soil community, and (at a larger scale) off-site resources such as forest litter.

Agricultural research is often restricted to the choices of farmers of crops or crop combinations and their management for maximum financial returns via harvested components. Yet, this is only part of the whole picture (Fig. 1): planned diversity and its management also influences ‘associated diversity’,

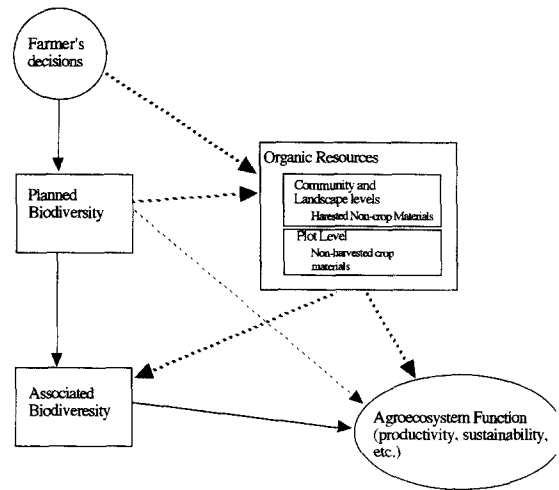


Fig. 1. The basic transformation processes in a multi-species agroecosystem as discussed in the present work.

and the non-harvested parts of the system may serve important functions as well.

The choices made with respect to the planned biota, together with crop and land management practices, influence the other organisms causing changes in their population structures and sizes. Changes in total (i.e., planned plus associated) biodiversity in turn influence various ecosystem functions including the processes of resource capture by the crops, susceptibility to pests and diseases, and ability to withstand environmental perturbations.

The complexity of agroecosystems is largely based on farmer decisions, both at the individual farmer level and the farming community level. Farmer decisions on complex agroecosystems may be categorized as choices on the ‘planned diversity’, on the management of ‘associated diversity’ and on the harvest of farm components (which may include elements of the ‘associated diversity’ category). Whereas the harvested components are directly linked to the way agroecosystems productivity is measured and evaluated by the farmer in the short run, the non-harvested components play a key role in the functioning of the agroecosystems, its sustainability and long term productivity, and its function to other parts of ‘society’ at large. For example, the maintenance of soil organic matter and a viable soil resource generally depends on sufficient organic inputs to the soil, which are non-harvested parts of total biomass production. Fig. 1 diagrams these key fea-

tures: (1) planned biodiversity, (2) associated biodiversity and (3) non-harvested components.

The key feature, from an ecological perspective, of multi-species agroecosystems is biological diversity. The implications of that biodiversity are complicated, as indicated above. Fig. 1 illustrates the various biodiversity transformations that appear to be important in assessing potential responses to global change. At the simplest level the farmer makes decisions that determine whether there will be trees in the system or not, whether and what kinds of animals will be included, how many crops to plant, etc. That is, the farmer plans the biodiversity to be included on the farm. Along with that planning, and partly a consequence of the planned biodiversity, the family or larger community will have access to various non-crop materials that may be utilized, either harvested (e.g., firewood) or in some non-harvested manner (e.g., use of trees as boundary markers). Furthermore, at the level of the farmer's plot a host of material that is not harvested (e.g., root material of annual crops, rotting wood of branches of fruit trees) will result. The planned biodiversity will give rise to an associated biodiversity, the host of weeds and beneficial plants that arrive independently of the farmer's plans, the soil flora and fauna that may respond to particular crops planted, the myriad arthropods that arrive on the farm, etc. Finally, the extra-planned organic resources, plus the planned biodiversity plus the associated biodiversity combine in a complicated fashion to produce the ultimate agroecosystem function, its productivity and sustainability. The manner in which these transformations occur can be thought of in three categories, as illustrated by different line styles on the arrows in Fig. 1: (1) functional attributes of planned biodiversity (solid line), (2) management decisions, system biodiversity and agroecosystem function (dotted lines), and (3) organic resources and sustainability (dashed lines). The remainder of this article assesses the state of knowledge about these three different categories, considers the tool-box available for making progress in research, and formulates conclusions on priority areas for further work. Considerations will be given to agroecosystems worldwide. For further study, however, a distinction will be made between situations where complexity is still high, and where real-world choices relate to the reduction of this complex-

ity, and situations where simplification may have gone too far and where issues revolve around a partial return of complexity. Large parts of the Temperate Zone fall in the latter category, with considerable parts of the tropics representing the first category. In between these two are 'landscape mosaics' where both types of issues are relevant.

2. Functional attributes of planned biodiversity

Much of current understanding about the functional attributes of planned biodiversity of multi-species ecosystems is derived from research on intercropping and agroforestry (Vandermeer, 1989; Ong and Huxley, 1996), which are almost exclusively based on mixtures of only two or three species and therefore might not be relevant to more complex ecosystems such as home gardens. The primary objective of such studies is to increase productivity and because most trials are based on the results of one or two seasons they do not provide a realistic insight into the resilience and sustainability of these systems. Information on the functional attributes of more complex ecosystems remains largely descriptive.

Early attempts by agronomists to discover the basis for the improved productivity of intercropping began by using many of the ecological techniques for investigating competition in natural communities (see reviews by Willey (1979), Vandermeer (1989), Francis (1986)). These studies provided an important step towards understanding the competitive performance of species in a mixture but did not directly deal with the way in which they influence ecosystem functioning. These competition studies gave rise to the concept of complementarity or competitive production which occurs when each species experiences less competition when grown with other species than when grown alone, paralleling the classic ecological concept of competitive exclusion (Vandermeer, 1981, 1989). Such a scheme enables, at least theoretically, the identification of species combinations that may be suitable for intercropping.

Research on ecosystem functioning in intercropping and agroforestry systems began in the late 1970s and early 1980s respectively, which focused on the interception and utilization of light in the

semi-arid tropics (Willey et al., 1986; Monteith et al., 1991; Ong and Black, 1994). The resource capture approach attempts to define complementarity in terms of the efficiency in which mixture of species capture and utilize limiting growth resources. In terms of available resources, complementarity occurs when a mixture of species results in the capture of a greater fraction or quantity of the limiting growth resources and/ or the more effective utilization of the same resource. Thus, in complex ecosystems increased resource capture may result from reduction of water and soil loss, utilization of off season rainfall where normal cropping is not possible, recycling of nutrients from deeper layers in the soil profile and other factors. The more effective use of captured resources may result from improvements in microclimate, greater light and water use efficiency and prevention of damage by strong winds or desiccation (see reviews in Ong and Huxley (1996)).

At present there are at least two schools of thought concerning the resource use of intercropping systems. The first assumed that a combination of two contrasting species, usually legumes/ cereals, would lead to greater overall biological productivity than each species grown separately because the mixture can use resources more effectively than separate monocultures (Willey, 1979, Willey et al., 1986). In recent years, this interpretation has been challenged on the grounds that in many instances the comparison with single species controls were inappropriate and that increased resource use is not a necessary condition for intercrop advantage over separate monocultures (Vandermeer, 1989; Keating and Carberry, 1993; Ong and Black, 1994). Frequently facilitation is involved, such as when one crop attracts natural enemies to the system and thus facilitates the escape of the second crop from some fraction of pest attack (Vandermeer, 1984, 1989). It has also been suggested that in such environments were productivity is more limited by water and nutrient supply than by the capacity of roots and leaves to capture resources, resource utilization can be readily optimized with two, or even a single species (Swift et al., 1996).

In contrast, evidence of increased resource use by agroforestry systems as compared to annual cropping is growing (Ong and Black, 1997). Several studies in both tropical and temperate environments have regu-

larly shown that greater capture of light, water and nutrients can explain the higher productivity of agroforestry systems over annual cropping although substantial competition between trees and crops may occur. These findings reveal two important differences between intercropping and agroforestry systems. Firstly, in intercropping systems the annual crops begin to produce their root systems at the same time, with the result that competition for below ground resources is less important than in agroforestry systems where the trees are well established and hence well placed to capture above- and below ground resources even before the crops have germinated. Secondly, the improvement in resource capture is primarily because of the deeper rooting of the trees, particularly after the crops have been harvested.

So what are the best prospects for complementarity in resource capture in multispecies systems? The current agroforestry hypothesis suggests that trees must utilize resources that the crop cannot acquire and/or provide substantial value per unit of resources obtained in competition with the crop (Cannell et al., 1996). Thus, the first step in any analysis of the potential for multispecies systems to increase productivity should be to determine whether the available growth resources are under-utilized by existing systems. If the existing growth resources are under-utilized because they are inaccessible to the root systems then deeper rooting would be an advantage. For instance, in the humid tropics the integration of trees in agricultural land use systems can substantially reduce nitrate leaching from the topsoil and prevent accumulation of nitrate in the subsoil (Van Noordwijk et al., 1992). However, according to Van Noordwijk et al. (1996) two major conditions need to be met for trees to act as nutrient pumps or safety nets. Firstly, the trees should have a considerable amount of fine roots at depth, which should contain substantial nutrient stocks. Secondly, water content at depth should be sufficient to allow diffusive transport to the roots.

Many challenges still lie ahead in extending the resource capture concept from the relatively few two or three species mixture in intercropping and agroforestry systems to the multispecies ecosystems that typify the vast majority of tropical agriculture. Perhaps more rapid progress could be made by focusing

on the similarity of plant responses and attributes rather than by preoccupation with the myriad of differences among these species. It is commonly assumed that the vast diversity of life forms in tropical forests contribute to their high resource exploitation, and research is currently underway to assess the connection between complementarity of resource use and the role of biodiversity in sustaining ecosystem processes (Haggard and Ewell, 1997). Early results for three fast-growing tree species and two understory perennial monocrops have confirmed previous findings of intercropping and agroforestry research that the potential for increased ecosystem productivity and resource capture occurs because of the inability of the dominant species to utilize available resources completely. This conclusion is consistent with the central hypothesis of agroforestry put forward by Cannell et al. (1996) that “trees must acquire resources that the crop would not otherwise acquire.”

Uncertainty of production conditions during a growing season can be approached by searching a robust (‘multi-purpose’) crop (cultivar) (an ‘integrated’ option), or by making use of a diversity of crops (or cultivars), which are complementary in response to the external source of variation (a ‘segregated’ option). The adage ‘don’t put all your eggs in one basket’ favors the second option, but there are no corresponding rules on how many baskets to use and how to distribute the eggs over them (Vandermeer and Schultz, 1990; Van Noordwijk et al., 1994). Yet, the diversity option to risk management leads to essentially different criteria for yield stabilization than the single-component option. Components with a high variability can be very valuable in the first approach, but they will be selected against in the latter. Selecting combinations of components with low overall variability can follow economic portfolio theories and use components on the basis of their co-variance in response to external sources of variation. Van Noordwijk et al. (1994) applied this concept to grain production in the Sahelian zone of Africa under uncertain rainfall and proposed a criterion for judging whether an additional new basket is worth using.

Plants can affect the functioning of ecosystems below ground via litter quality, the quantity and

timing of litter inputs, rhizodeposition, through the soil water balance and microclimate near the soil surface. Plant diversity can lead to a wider array and/or a more continuous supply of directly soluble carbohydrates stimulating the microflora, the more structural components providing supporting the activities of soil fauna and the products of decomposition contributing to soil organic matter formation. In return, the below ground community provides a number of ‘environmental services’ for the plants in terms of a favorable soil environment for root development, and water and nutrient availability. The controls over water flux pathways, nutrient mineralization and decomposition are broad-based and there is little evidence that more diverse systems (either in terms of plant resources or in terms of the biodiversity of soil organisms) function better in supporting plant production provided that the minimum suite of functional groups is present (Anderson, 1994). Current models of below ground food-webs are reasonably successful in predicting the time pattern of N mineralization for a given structure of the food web and abundance of functional groups, but even in the most intensively managed and simplified agroecosystems mineralization of organic residues still functions (De Ruiter et al., 1995; Anderson, 1994; Swift et al., 1996). Specific relations occur in the symbionts, diseases and their antagonists and it is here that below ground diversity may facilitate above ground diversity.

Causal links between above ground (plant) diversity and below ground biodiversity are likely to exist, but probably involve considerable time lags. Little is known of how long it takes for the below ground ecosystem to respond to even such drastic changes as a conversion of forest to crop or grassland. For re-introducing above ground diversity (‘rehabilitation of degraded lands’) the lack of specific groups of soil organisms may limit potential above ground (plant) diversity, but little hard data exist. Functional relations between above- and below ground biodiversity, mediated by roots, are likely to involve time-lags and may show ‘hysteresis’. Soil organisms tend to have less effective means of dispersal and may thus become a rate-limiting step for ecosystem adjustment in as far as they are critical for the functioning of above ground vegetation. This is most likely to be

the case for specialized obligate symbionts such as mycorrhizal fungi and specific rhizosphere organisms.

There is little detailed evidence that an increase in agricultural intensification (in a broad sense, including extending the time that the land is cropped, higher usage of fertilizer, pesticides, mechanization and/or control of soil water content by irrigation and drainage) results in a further loss of microbial biodiversity in soil once a particular pattern of cropping practice is established (Giller et al., 1997). Soil macrofauna, such as earthworms, are more susceptible to changes in soil management and the effects on soil properties of eliminating or reintroducing a single species representing key functional groups affecting soil structure and organic matter turnover are well documented (Lee, 1985; Anderson, 1994). Fragoso et al. (1997) describe a notable exception where the conversion of tropical rainforest to pasture in the Amazon basin resulted in large population increases in a single surviving species. As a consequence of massive surface casting activity depositing fine textured material on the soil surface the soils became compacted and pasture productivity declined. In other cases, soils can be mistreated to a remarkable extent and yet crops continue to support crop yields close to their theoretical maximum. Thus, not only is there no clear link between agricultural intensification and simplification of complex agroecosystems and a loss of below ground biodiversity, the consequences of any such loss await detailed investigation; concepts and methods for such study are well defined (Giller et al., 1997).

3. Management decisions, system biodiversity and agroecosystem function

Fig. 1 illustrates the relationship between farmers' decisions, planned biodiversity, associated biodiversity and ecosystem function. It has been repeatedly reported that associated biodiversity is positively related to planned species diversity in the case of vertebrates (Mellink, 1991; Perfecto et al., 1996; Pain and Pienkowski, 1997), arthropods (Perfecto et al., 1996; Perfecto et al., 1997; Perfecto and Vandermeer, 1994; Perfecto and Snelling, 1994;

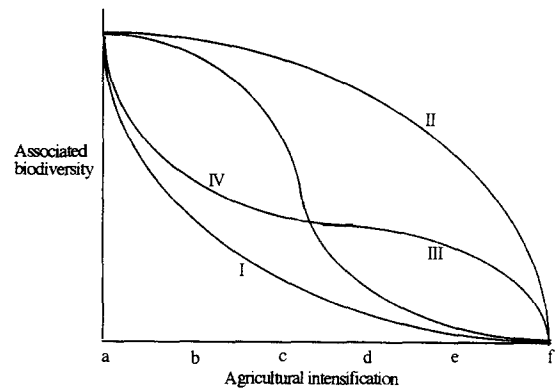


Fig. 2. Possible scenarios for the relationship between degree of intensification and total biodiversity. The intensification gradient moves from a = an unmanaged system (e.g., forest, grassland) b = Casual management (e.g., shifting cultivation, nomadic pastoralism, home garden), c = Low intensity management (e.g., traditional compound farm, rotational fallow, traditional agroforestry), d = Middle intensity management (e.g., horticulture, pasture, mixed farming, traditional cash cropping), e = high management (e.g., crop rotation, multicropping, alley cropping, intercropping), f = Modernism (e.g., plantations and orchards, intensive cereal and vegetable production). Pattern I is where any extent of human intervention drastically reduces biodiversity with added effects being relatively minor and progressive. Pattern II is where intensification affects species diversity only at very high levels. Patterns III and IV are intermediate relationships.

Hawksworth, 1991; Lefeuvre, 1992; Crossley et al., 1992; Dennis and Fry, 1992; Paoletti and Pimentel, 1992; Kim, 1994; Burel and Baudry, 1995; Black and Okwakol, 1997), soil microbes (Hawksworth, 1991; Olembo and Hawksworth, 1991; Anderson et al., 1992; Pimbert and Rajan, 1993), earthworms (Fragoso et al., 1997), and non-crop plants (Van der Maessen, 1993; Pimbert and Rajan, 1993; Losch et al., 1994; Chacon and Gliessman, 1982). However, it is almost certain that this relationship is non-linear (Fig. 2), although the exact form of this non-linearity remains to be investigated (Perfecto et al., 1996; Perfecto et al., 1997; Swift et al., 1996; Pimbert and Rajan, 1993). Although a certain number of associated species are likely to be incorporated into the system with the addition of each planned species or variety, it is also likely that the combination of planned species will create additional habitats for various associated species (Perfecto and Vandermeer, 1996), and possibly change the nature and

intensity of interactions among the associated species thus possibly reducing competition or predation coefficients to allow more species coexistence (Perfecto and Vandermeer, 1994).

On the other hand, it is well-known in general ecology that structural diversity can be a more important determinate of biodiversity. For example, MacArthur and MacArthur (1961) demonstrated that the number of bird species was more closely related to the structure of the habitat than it was to the actual number of plant species contained therein. It may be the case that in many of the studies cited above, increased planned biodiversity may bring with it increased structural diversity, thus confounding the observed relationship between planned biodiversity and associated biodiversity. An agroforestry system with a single species of tree is likely to harbor more arboreal beetle species than a pasture with 50 species of grasses and herbs.

Exactly how associated biodiversity is determined by the planned biodiversity is an open question, and probably is variable depending on agroecosystem and taxa involved. However, many comparisons of industrial-type agriculture with a more ecological agriculture suggest that the more ecological forms with their usual incorporation of more planned biodiversity, usually also have higher associated biodiversity (Paoletti et al., 1992; Gall and Orians, 1992; Ryan and Stark, 1992; Vandermeer, 1996), with some exceptions. Microbiological biodiversity is either greater in more ecological forms of agriculture, including minimum tillage (Liljeroth et al., 1990; Boehm et al., 1993; Frostegård et al., 1993; Kirchner et al., 1993; Kennedy and Smith, 1994; Workneh and van Bruggen, 1994; Zelles et al., 1994) or no significant difference is found (Buyer and Kaufman, 1996; Doran et al., 1987; Hassink et al., 1991). Termites have been reported as either increasing or decreasing in species numbers associated with the change from a natural ecosystem to an agroecosystem (Black and Okwakol, 1997).

However, the transformation of planned biodiversity into associated biodiversity is only the first step in the conversion of biodiversity into ecosystem function. It seems that there are two conflicting points of view regarding the function of associated biodiversity. Some presume that the various species or genotypes perform various functions all of which

are necessary for the proper functioning of the ecosystem, and thus a higher biodiversity implies that all of the necessary functions will be served (Erlich, 1988; Hawksworth, 1991; Wilson, 1988; Potter et al., 1990). For example, when the litter-eating earthworm fauna was eliminated from tea-gardens in India, large quantities of leaf litter built up on the soil surface (Senapati, 1994). An alternative view is that there is indeed a great amount of redundancy and relatively few functions to be served, and that an efficient system is one in which the 'best' species or genotype dominates in the performance of that function. For example, Hawkins (1994) reports that there is no evidence that two species of biological control agents operate better than a single one, implying that it makes sense then to look for the individual species that performs best. Materon et al. (1995) note that native Turkish varieties of *Rhizobium leguminosarum* generally perform poorly and suggest a program of active inoculation which is designed to reduce effectively the natural biodiversity of *R. leguminosarum*. This position is increasingly gaining credibility, especially among soil microbiologists (Anderson et al., 1992), although the positive attributes of ecosystem function enhancement of biodiversity is still probably the most commonly held position (but see Materon et al. (1995) who suggest a negative function of some biodiversity). Meyer (1994), for example, suggests that a large number of different types of bacteria are necessary to break down the various polymers in organic matter.

In contrast to the observation that a single biological control agent is as good as two (Hawkins, 1994), Levins (1986) has suggested that in an indirect way the inclusion of a generalist as well as a specialist natural enemy in a biological control system theoretically may be useful in that the generalist may effect control during normal times while the specialist is able to respond quickly to population flushes of the pest. Furthermore, the entire history of the emergence of new pests and resurgence of old ones (vandenBosch, 1978) suggests the need for a range of potential natural enemies waiting in the wings in anticipation of problems that may not be actualized in a particular moment, but may emerge in the future. Similarly, the various genotypes of *R. leguminosarum* may perform differently in different environments so that assessments during one or a few

years may not encounter that particularly wet (or dry or windy or sunny) year in which one of the poorly performing strains actually performs better. In this sense the biodiversity is seen as a hedge against future changes in environment, be they naturally occurring fluctuations or human induced.

The actual functions of associated biodiversity are either well-known or assumed in several cases, including the achievement of greater resource use efficiency, overcoming physical constraints to productivity and sustainability, and the achievement of stable and sustainable resistance to biotic stresses (Spain et al., 1991). The case of biological control of pests and diseases implies the existence of a diverse set of natural enemies that can serve this function (Altieri, 1991a,b, 1993; Waage, 1991; Kogan and Lattin, 1993). Other functions of insect biodiversity include pollination (Pimbert and Rajan, 1993; O'Toole and Gauld, 1993; Schwenninger, 1992; Batra, 1995), contributions to soil dynamics (Stork and Eggleton, 1992) and even as alternative food sources (De-Foliart, 1995).

It has long been assumed that biodiversity is generally a stabilizing force in ecosystems (MacArthur and MacArthur, 1961), an assumption that has led to attempts at suggesting a similar function in agroecosystems (Willey, 1979; Vandermeer and Schultz, 1990). But this particular assumption does not stand the test of careful analysis in ecology generally, as attested to by May's famous demonstration that larger more complex ecosystems tend to be less, not more, stable (May, 1974). Part of the problem is in the definition of stability and other measures of ecosystem processes in the first place, but nevertheless, the message from theoretical ecology is that there is no reason to expect that biodiversity as such will generate more productivity, resiliency, stability, or sustainability. Indeed, in at least one study (Anderson, 1994) it has been shown that conventional measures of ecosystem processes such as production, water balance, and nutrient cycling, show just as high levels of functional integrity in monospecific systems as in highly diverse systems.

However, it is almost certainly the case that the particular way in which biodiversity is organized in an ecosystem may indeed produce desirable effects in ecosystem properties (Pimm, 1982; Pimm et al., 1991), a principle that undoubtedly applies to agro-

ecosystems as much as non-managed ecosystems. Existing complex agroecosystems are not random combinations of components. They have survived under continuous selection by the farmer to improve on low-value components. Broad statements relating internal diversity and complexity to an expected increase in resilience and stability are difficult to test specifically, because so much depends on the specific biological relationships among the components. Changes in the system, such as the removal or addition of trees leading to a change in microclimate may reduce some problems while enhancing others. Furthermore, biodiversity differences may reflect other environmental differences that are the real driving forces of some ecosystem function, much as has happened in recent attempts at manipulating biodiversity in experimental situations (Huston, 1997). Although it can already be said that clear empirical evidence exists for both the positive and negative effects of some biodiversity components (see above), it is hardly worthwhile to score the number of pluses and minuses in the literature. The important goal is to make predictions for any specific situation, a goal that requires more detailed understanding than is presently in our tool box.

In sum, there appear to be three hypotheses about biodiversity and agroecosystem function: (1) Biodiversity enhances ecosystem function because different species or genotypes perform slightly different functions (have different niches) and all together function better than some subset. (2) Biodiversity is neutral to negative in that there are many more species than there are ecosystem functions and thus redundancy is built into the system. (3) Biodiversity enhances ecosystem function on a long-term basis because those components that appear redundant at one point in time become important when some environmental change occurs, which is to say the apparently redundant species are in fact ecosystem buffers. A corollary to the redundancy hypothesis is that one species is likely to be the most efficient at performing the particular ecosystem task, and all the other members of the redundant set are at least slightly less efficient, suggesting that biodiversity should actually be decreased so as to give preference to the best species. This last position has precedence not only in recent technical literature [e.g., Varney et al. (1995) recommend spraying the herbicide Clodi-

nafop-propargyl on conservation headlands to eliminate the highly competitive grasses], but in the literature on traditional agricultural systems [e.g., Chacon and Gliessman (1982) report that Mayan farmers look at some plant species in their fallow as good components of the fallow and thus deserving of conservation with other components considered bad and thus deserving of removal].

There are thus some obvious situations in which the function of having more rather than fewer species is obvious (see above), other cases in which ecological theory or natural history common sense would dictate that more species would be better, but for the most part the function of biodiversity is not known for sure. On the other hand, the diversity of opinion about biodiversity's function is high while the data base on which a solid judgment could be formulated remains sparse, as has been noted previously (Giller

et al., 1997; Swift and Anderson, 1994; Swift et al., 1996). Any of the three general positions could be correct for any particular situation and further study is awaited to provide guidance as to what situations each of the positions applies.

4. Non-harvested components and sustainability

Non-harvested components (NHC) are key elements of agroecosystems which provide the habitat and resources for the associated species which maintain many critical agroecosystem functions. The NHC also determine biophysical parameters such as microclimate, ground cover and soil properties, which affect erosion, water balances and nutrient retention (Table 3), and hence the long term sustainability of crop production.

Table 3
Functions maintained by non-harvested components of plants in farming systems

Component of non-harvested biomass	Agroecosystem function
Trees	Shade Aesthetics Habitat for diverse associated biodiversity of fauna, flora and microbes Wind breaks Litter (with similar functional attributes to crop residues) Affect on local and catchment hydrology Maintenance of soil fertility (e.g., <i>Acacia albi</i>)
Weeds and cover legumes	Capture of plant nutrient excess (e.g., in fallow period) Protection of soil surface against splash erosion; improved infiltration Habitat and resources for associated biodiversity (pests, pathogens and their control agents) Resources for soil organisms mediating soil processes Nitrogen fixation by legumes Creation of microclimate and reduction of wind speed of boundary layer Entrainment of wind and water-borne sediment
Crop residues	Dung from domestic stock increases plant nutrient availability Effect of mulching on soil temperature and moisture Protection of soil surface against splash erosion, improved infiltration Habitat and resources for associated biodiversity (Beneficial soil organisms, pests, pathogens and their control agents) Nutrient carry-over between crops Microbial products promoting aggregate stabilization Maintenance of soil organic matter
Roots	Dung from domestic livestock Binding soil structure Creation of macropores and water conduits Contribution to soil organic matter Nutrient carry-over between crops Resources for beneficial and plant pathogenic soil organisms

The shift from traditional to high technology farming systems, associated with the intensification of crop production, has generally been accompanied by reduction in the diversity of ecosystem types in the landscape, reduction in woody vegetation cover and increased area extent of arable monocultures. In traditional shifting agriculture and agri–pastoral systems, cultivated plots form small islands within the natural vegetation and the community often gathers a wide range of non-staple foods and other natural resources from the surrounding forest and grassland. At the other extreme, under highly intensive agriculture, the whole landscape may be dominated by a single monoculture of hybrid maize, wheat or irrigated rice and other natural resources are acquired through the market economy.

In parallel with the reduced diversity of crop plants with increasing intensification of cultivation, the harvested biomass as a proportion of total plant biomass also increases from the traditional systems where tree crops and non-timber products are important resources in the local economy, to intensively grown cereal monocrops where harvested grain can amount to half of above ground biomass.

One consequence of this shift in the yield/total biomass ratio towards intensively cultivated, arable monocrops is a potential change in the stability and resilience of the utilizable resources. Basic food resources in traditional rain fed systems appear to have greater potential stability and resilience to climatic perturbations, such as drought. Communities of natural species in semi-arid, drought-stressed, regions have been selected for persistence. Hence the diversity of traditional food plants, which may include less-palatable tubers and other natural products which are not usually harvested, provide a spectrum of ‘back-up’ resources which are collectively less affected by climate perturbations than arable crops. The high NHC of woody biomass of forest and tree savanna systems also represents a natural resource capital which can be drawn on more intensively for browse and fuel at times of need. The ratio of resource utilization to plant production is obviously critical, however, and in many semi-arid areas of Africa and Asia continuous demand for fuel exceeds production by woody biomass so that crop residues, dung and even roots may be removed and burnt.

Intensive arable monocrops are potentially more susceptible to perturbations in climate and global economics but are buffered by technology, such as irrigation, and financial capital (Swift et al., 1996). In developing countries most small-holder farmers have not had the land tenure, financial security and market opportunities to risk investment in extensive production of high yield crop varieties and these cultivars are commonly restricted to niches with better soil and available water within multispecies cropping systems. It is increasingly recognized by national and international development agencies that the provision of rural credit systems, access to agrochemicals, better extension services and introduction of new stress tolerant crop cultivars (including more systematic breeding from traditional landraces) is required to ensure food security, improve rural economies and a higher quality of life for significant components of the global population. This trend towards intensification of crop production, or the rehabilitation of degraded systems, raises critical issues of the roles of the NHC in agroecosystems and what levels of these resources must be left unexploited to maintain key system functions.

4.1. Functional attributes of non-harvested biomass

The main components of non-harvested plant biomass in agroecosystems, trees, weeds and ground cover species, crop residues and roots (Table 3) have properties which are not necessarily linear functions of the attributes of the individual resource components. For example, the microclimate of a forest has higher order properties than individual trees; it is not the individual trees which create the modified environment but the spatial arrangement of the trees. Similarly, as considered below, control of splash erosion is a function of the mass of ground cover in relation to the erosivity of wind and rain rather than the diversity of individual resources. However, the geometry of the trees, ground cover or mulches, and their persistence over time, can be important in determining the level of resources required to maintain a particular function. On the whole, these attributes of NHC have not been defined or applied to define algorithms which can be used as tools for defining critical thresholds for the take off of plant biomass and the design of agricultural landscapes.

4.2. Trees, microclimate and shelter-belts

Trees are often planted around homesteads and field margins for aesthetic and cultural values, fruit production, shade and wind protection. Shelterbelts can also indirectly affect the adjacent crop. Kowalchuk and Dejong (1995) showed that in years with average or below average rainfall, in Canada, yields of wheat were depressed within 10 m from shelterbelts of trees about 6 m high but slightly enhanced 10–20 m out into the field. The edge effect appeared to be related to reduction in evapotranspiration on the lee side of the shelterbelt and was absent in years when water was not limiting during the growing season. Eucalyptus planted along field margins in the savanna zone of Nigeria were similarly shown to have a moderating influence on windspeed and evapotranspiration by crops to 15 times the height of the trees (Ujah and Adeoye, 1984). Millet yield was higher in the sheltered area than in the open with peak yields at four times the tree height. The general principles of agrometeorology are well established for managing crop microclimates and wind erosion but the benefits can also be linked to the distribution and dispersal of pest species and their control agents within field systems.

4.3. Grass bunds, weeds and ground cover

Grass bunds, ground cover and weeds maintain a multiplicity of functions in agroecosystems (Table 3) which can have positive or negative benefits to the farmer. Grass bunds (with or without hedgerows) are commonly established to stabilize terraces and paddies, and for erosion control on slopes. The area given over to bunds and hedgerows can provide important auxiliary resources but reduces the cultivable area. Semwal and Maikhuri (1996) show that in the irrigated valleys of the Himalayan foothills grain production was high but people were forced to rely on forests for fodder and fuel wood which were some distance from the homesteads and required considerable effort for harvest. On rainfed terraces, grain production was lower and more seasonally variable but valuable green biomass could be harvested from trees, weeds and grass growing on bunds. Cost benefits of weed control in the Punjab (Aggarwal et al., 1992) have shown that where a farmer

requires fodder and rice then harvesting both components is as profitable as intensive weeding and harvesting only the grain. This analysis does not include the trade off between the two strategies in terms of soil fertility maintenance which could critically depend on the efficiency with which dung derived from the herbage and straw was returned to the field plots.

Fast growing legumes, such as *Centrosema*, *Pueraria* or *Mucuna* are generally seeded as ground cover in oil palm, rubber and coconut plantations in the humid tropics. Legume cover is established after clearing natural forest, or old plantations, to reduce erosion, suppress weeds and supplement inorganic fertilizer applications by nitrogen fixation (Broughton, 1977). The addition of one species of ground cover legume therefore meets several functional requirements in the system. Tree plantations with well established legume cover have a very similar microclimate to natural forests and maintain a diverse soil fauna community containing many elements of the system from which it was derived. The higher quality organic matter inputs may, however, favor some exotic species of earthworms which achieve a high biomass and have significant effects on soil structure, organic matter turnover and nutrient dynamics (Lavelle et al., 1994).

Soil losses in surface runoff are generally small under undisturbed vegetation cover. But when cover is removed there is usually a rapid onset of sheet erosion caused by raindrop impact breaking down soil surface aggregates and blocking macropores. Under trees, this relationship between canopy cover and erosion is quite complex because the structure of the vegetation profile determines drop size and the kinetic energy imparted by the distance the drop falls before impacting the ground. Similar values were recorded for the erosivity of throughfall in a bamboo plantation and the complex vegetation profile of a home garden in Java suggesting that species diversity was a relatively unimportant variable compared to vegetation structure. The experimental removal of tree canopies has shown that little splash erosion occurs if the soil is protected by a thin but continuous cover of ground vegetation or litter (Nortcliff et al., 1990). In contrast, rangelands subject to lower intensity storm events exhibit little erosion until the ground vegetation is reduced below about 20% cover (Mbakaya et al., 1988).

4.4. Crop residues

The retention of above ground residues and roots of crops on field plots is critical for the maintenance of soil fertility. These resources support a number of key functions (Table 3) notably the biophysical effects of mulching on soil microclimate and erosion control, maintenance of soil organic matter (and associated properties), plant nutrient supplies and resources for the soil biota. The amount and location of these residues required to maintain these functions depends on the soil type and environmental conditions. Roots may be particularly important for maintaining soil fertility if there is large removal of above-ground residues. Grain harvest of short straw cereals can be as much as 50% of the above ground biomass at the time of harvest and 80–90% of peak standing crop may be removed for hay or silage in intensively managed pastures. However, in both systems roots may comprise 50% or more of net production and have a much higher contribution to soil organic matter formation than residues surface applied as mulch or incorporated by tillage.

Increasing concern over soil degradation in most regions of the world is reflected by the burgeoning literature on organic matter management and conservation tillage practices. Much of this research effort is, however, directed at fragile soils of the temperate and sub-tropical regions, mainly extensive cereal production systems in Australia and North America, rather than small-holder farming systems in the tropics. The processes and process controls are universal but the rate determinants, particularly the lower amounts of resources to conserve soil fertility under more severe environmental constraints, are largely unquantified.

Maintaining crop residues on the soil surface during fallow periods to conserve fragile soils against wind and rain erosion is a common practice in most farming systems. Standing stubble changes the aerodynamic properties of the boundary layer at the soil surface and reduces wind erosion (Sauer et al., 1996) so that as little as 4% ground cover can reduce wind erosion by 15% compared with bare soil (Fryrear, 1995). The use of herbicides during fallow periods has not been found to affect soil erosion because the weed control still maintained anchored residues and soil cover (Oltjen and Beckett, 1996). The value of

surface mulching to reduce splash erosion, insulate the soil and conserve moisture is well understood. Bussiere and Cellier (1994) have developed a model relating mulch cover and water and energy exchanges with the atmosphere and concluded that a mulch leaf area index of 4.0 limited evapotranspiration but intercepted more rainfall so that a LAI of 1.0 optimized soil water conservation. Depending upon slope, soil texture and rainfall intensity the geometry of the mulch (e.g., palm fronds vs. straw vs. twigs) and also the rate at which the material decomposes during the wet season (Schomberg et al., 1996). Soils are vulnerable to splash erosion under slow-growing crops, such as cassava which has an open canopy for the first 3–4 months after planting, but soil losses were found to be three times lower under mixed cropping with maize or sweet potatoes (Aina et al., 1979). Arable crops which are fast growing rapidly establish closed canopy cover, like legume ground covers, which protect the soil and reduce the necessity for mulch as a soil protection measure.

The amount of soil organic matter (SOM) required to maintain soil fertility is extremely difficult to define because of the multiplicity of functions affected and the operation of other constraints when SOM is not limiting. In intensive rice production systems, where the paddies are more or less continuously flooded to achieve three crops a year, some recent declines in yield may be the consequence of nitrogen immobilization by the large pools of soil organic matter precursors formed under anaerobic conditions (Olk et al., 1996). A reduction of organic matter inputs or an aerobic phase in the cropping cycle under beans or wheat may be required to optimize crop yields. In many temperate regions the large pools of stabilized SOM may be relatively unaffected by removal of crop residues providing that fertilizer inputs were maintained (Stumborg et al., 1996), suggesting that root carbon was more important than straw for maintaining SOM. However, soil biological parameters, such as microbial biomass, are sensitive indicators which respond rapidly to residue inputs and management (Karlen et al., 1994). Hendrix et al. (1986) have shown that the composition of soil organism communities, and associated functions such as aggregate stability, organic matter incorporation, rates of nutrient turnover and the effects of earthworms on surface water infiltra-

tion, can differ widely under different conservation tillage practices. However, the amount of residue input required to maintain these functions has not been investigated.

Current inputs of organic materials (and fertilizers) to cropped lands are generally insufficient to arrest the decline in soil organic matter when natural systems are converted to permanent agriculture, either because of low residue production, or demands for fuel and fodder, or commonly a combination of both. Powell and Hons (1991) found that SOM rapidly declined when residues were removed from sorghum fields in the Sahel because of the high rates of C mineralization when moisture was not limiting during the growing season. More research is needed on efficient ways of utilizing such scarce resources in space (minimum ground cover, residue architecture, crop types) and time (ground cover in relation to rain and wind events, decomposition of residues in relation to crop cover). Also, because of the plurality of functions served by crop residues the tradeoff optimal for erosion control, moisture conservation, nutrient supplies and promoting soil biota, must be determined. This integrative approach for the tropics requires on-farm participatory research to draw on the wealth of experience which small holder farmers have on risk management. For example, a survey by ICRISAT in the Southern Sahelian Zone (Lamers et al., 1995) showed that although 66% of farmers noticed wind erosion on their farms it was not of major concern. As and when local areas suffered wind damage, farmers used stover from the more productive areas, at local application rates equivalent to only 2 t ha^{-1} , to control erosion thus effecting a much more conservative use of resources than a precautionary approach to soil conservation.

5. Roles of different types of models in complex agroecosystem analysis

For answering questions on the likely performance of single crops, a considerable convergence of models has taken place, and comparisons can focus on model performance in actual production trials. For dealing with more complex agroecosystems, we remain largely in the stage of developing conceptual models. Although the complexity of multispecies

agroecosystems is intimidating, accumulated knowledge is now at a level where more quantitative models may be useful. Models of agroecosystems can be developed to answer a wide range of questions, differentiated by spatial and temporal scale. Predicting the productivity of a cropped field is only one of many aspects—although one could argue that it is of prime importance to the farmer. Other factors, such as secure land tenure and risk reduction, may also be important to the farmer, yet are far more difficult to incorporate into typical modelling platforms.

The sheer number of components automatically limits the style with which models can be developed in multi-species agroecosystems. Suppose that one wants to develop a ‘blue-print’ of a multi-species agroecosystem. There is a choice of Z trees, Y crops, X spatial arrangements of trees and crops, W temporal arrangements of the components, V animal components, U choices for other inputs, T time frames on which to evaluate the results, S ranges of soil conditions, R climatic zones, Q farmer preferences, P policy environments, O objectives to evaluate system performance, N sets of natural enemies, pest and disease pressures, M sets of market conditions, L situations of labor supply, K sets of indigenous knowledge, etc. Certainly, this is far too complex to model with a brute force ‘boxes and arrows’ mentality. Yet, this is also far too complex to deal with by trial and error. Imagine a $K * L * M * N * O * P * Q * R * S * T * U * V * W * X * Y * Z$ type factorial design, even allowing, for only two levels per factor. In modelling and experimenting with multi-species (or complex) agroecosystems it may be futile to attempt the same level of precision and the same scope for ‘optimization’ as in research aimed at the management of a single crop (Vandermeer et al., 1984).

Yet the problem is significantly worse than implied with this simple example. Although the monoculture crop models proceed under the assumption that the environment has been greatly simplified (which is in fact the case for the situation being modelled), multispecies agroecosystems must incorporate two profoundly complicated subsystems, neither of which has ever been adequately modelled—the ecosystem and the human social system. While we must acknowledge all of the complexity of

Table 4
Targets of models dealing with issues of global change in multi-species agroecosystems

Time scale	Spatial scale		
	Field	Farm	Landscape
Short	Average plot yield	Neighborhood effects, lateral-resource flow and capture	Scaling rules, non-linear responses, lateral resource flow
Medium	Variance reduction by diversity	Farm management	Economic geography
Long	Attractor domains (non-linear responses)	Land use change	Real world

ecosystem models, with species interactions, multiple species utilization of resource pools, multiple trophic levels and the like, we must also incorporate human factors such as the farmer's ability to predict future markets, the farming community's characteristics that determine local markets, the local economic and social forces that dictate which crops will be grown when, and a host of other ill-defined state variables and attendant dynamic rules. Indeed, although it is commonly thought that the agroecosystem is a simplification of a 'natural' ecosystem, from this point of view we must deal with both the complexities involved with trying to understand an unmanaged ecosystem, yet add the remarkable complexity of the human system on top of that. It would appear that the agroecosystem, from this point of view, is even more complicated than the unmanaged ecosystem.

For example, the first phase of the 'Alternatives to Slash and Burn' project in Indonesia came to the conclusion (Tomich et al., 1998) that the development opportunities of more productive agricultural systems is a double-edged sword from the perspective of protection of remaining forests and their environmental values. On the one hand, more productive alternatives can allow intensification on part of the land and allow for conservation of environmental values elsewhere. On the other hand, productive options can serve as a magnet attracting migrants from elsewhere, who will cause an increased rate of forest conversion. The likelihood of migration flows depends on opportunities for unskilled labor elsewhere in the economy, on the accessibility of the area as influenced by the infrastructure and on the effectiveness of local and national regulations of access.

Because of this overwhelming complexity, multi-species agroecosystems are obvious targets for

large-scale simulation-type models. Unfortunately, casting such models at the same level as the well-known monoculture crop simulators (nutrient and physical parameter inputs and physiological functional definitions) is not likely to be very successful, for it will inevitably miss many salient features (land tenure and the risk of draught are not conveniently linked with carbon fixation). The successes of the monocrop models should thus not be taken as an indication of the direction that models of multi-species agroecosystems should take.

At the other extreme, models of aggregated variables, whether formulated quantitatively or qualitatively, have in the past provided important insights about multispecies agroecosystems. The problem with such models is that they are not usually capable of providing precise quantitative predictions and thus are unlikely to provide a springboard for making quantitative predictions associated with various scenarios of global change. Yet they have in the past provided certain insights (Vandermeer, 1997; Van Noordwijk and de Willigen, 1986) and it is anticipated that they will continue to do so in the future. Such models, unfortunately, are likely to continue representing only small subcomponents of the systems we seek to understand.

As a first approximation, the authors present a potentially useful scheme for thinking about model development in the context of multi-species agroecosystems (Table 4). This scheme could apply to either large-scale system-type models or more qualitative models with aggregated variables.

6. Conclusions

The consequences of global change are not likely to be similar in all agroecosystems. Especially im-

portant are the differences expected between conventional monocultural-based agriculture, where already sophisticated models are available to enable researchers to simulate scenarios, and multi-species agroecosystems, where even initial conceptualization is at a primitive level and those models that have already been developed are either qualitative and conceptual, or restricted to a small subset of the overall system (e.g., Trenbath and Stern, 1995; Vandermeer, 1986). Yet it is arguably even more critical to understand the effect of global change on these later agroecosystems, because they are characteristic of the vast majority of the world's farmers.

The authors have proposed a scheme for analyzing multi-species agroecosystems (Fig. 1) in which the plans of the farmer are translated into ecosystem function through the modification, intentional and unintentional, of system biodiversity. Although biodiversity is the most obvious feature of multi-species agroecosystems, its particular function in ecosystem processes is still enigmatic. At one extreme it would appear that much redundancy is built into ecosystems and key processes are carried out as well in monotonous systems as in highly diverse systems, yet for some functions (i.e., system resilience) it seems that biodiversity plays a key functional role.

Whatever the particular role of biodiversity in agroecosystem function, it is clear that two components of this variable exist—the planned and the associated. The associated biodiversity is frequently overlooked by analysts concerned with farmer choice. Yet it is now clear that the associated biodiversity may be very large in less intensive systems, although its function remains unknown in all but a handful of cases. Learning the mechanisms through which the associated biodiversity is determined by the planned biodiversity is a key research priority.

A key component of the associated biodiversity is the multifarious non-harvested components of the farm, so especially important in highly integrated agricultural systems. Although these components may go overlooked by technical analysts, and not even mentioned in interviews with farmers, they are nevertheless sometimes critical for maintenance of multi-species systems. They may function as determinate forces in ecosystem dynamics as well as in the socio-political infrastructure of the farm or farming community.

Much research in agriculture has been focused almost exclusively on production. Equally as important as productivity per se is the sustainability of the system in the face of change; agroecosystems must have the capacity to either resist the effects of large perturbations or rebound from them—a key attribute for global change considerations (Lyman and Herdt, 1989). System resilience is the ability of a system to overcome perturbation and to recover function to former levels once the perturbation is removed. It may be expressed as the time necessary for a system to re-establish the status quo. Examination of the resilience of systems in response to global change is as important a component of research as measurement of trends in productivity, although far more difficult. It has a particular significance in that system resilience may be a property particularly valued by the farmer to whom concerns over risk reductions are as important as yield trends.

The definitions currently used for agroecological zones are largely based on rainfall and temperature and may be relevant for the evaluation of single crop production opportunities. Natural resource management issues, however, include environmental functions of land use, as well as a strong human dimension. A more meaningful identification of agroecological zones and extrapolation domains should include socioeconomic parameters and indicators of development (population density, market integration, infrastructure, wage levels) and environmental functions (biodiversity conservation, reducing net GHG emissions, watershed protection). Establishing operational classification systems which can indicate which ones of the biophysical production opportunities may indeed be feasible and desirable in various parts of ecoregional zones remains a major challenge. Whether or not real world systems take notice of such desirabilities depends on how decision-making power is distributed in society.

Understanding of modern monocultural systems have been obtained largely through the application of physiologically based models with biophysical forcing factors. In the case of multi-species systems there is a human dimension that complicates the problem considerably. The 'human dimension' indicators have a more dynamic character than the biophysical ones, and, especially where long-duration tree crops are involved, some prognosis of future sociopolitical

developments must be incorporated into the evaluations of current land use options.

For multi-species systems, land use practices must be evaluated as ‘multiple goal’ operations. A major dichotomy is between ‘segregation’ and ‘integration’ of functions as a means to achieve multiple goals. To analyze these options at a range of scales and from the perspective of a range of actors (farmers, local–national government, international bodies), information on trade-off is needed among the various functions.

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