Chapter 6

Ecosystems and Ecosystem-Based Management

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Within the complex adaptive systems (CAS) framework, working at the ecosystem level requires actions across large scales over time as well as space. Processes such as water and nutrient cycling, soil formation, and desertification take place over much more than a few years and across areas that can encompass an entire continent and surrounding oceans. Because most human actions occur at a certain time and place but with consequences occurring far beyond that moment and place, an effective adaptive management process requires us to continually look back and forth, from local to regional scales, and from short to long time frames. In this chapter, we will follow three basic principles for sustainable management:

- We focus on the long-term and regional scale.
- We value diversity in systems (biological and social/cultural).
- We believe that the more closely human activities resemble natural patterns and natural disturbance regimes (such as fire frequency) the more sustainable the system is likely to be.

In the earlier description of the scalar dimensions of the Sustainable Agriculture and Natural Resource Management landscape system (see chapter 1), we define the ecosystem as the system that encompasses the field, farm enterprise, and watershed systems and that operates on a similar scale with policy and markets most effectively for sustainable management. Before effectively working in a CAS framework, it is necessary that we understand the origins, varied definitions, and properties of this ecosystem-level concept.

The concept of the ecosystem arose early in the science of ecology as a logical extension of the debate at the time over how communities of organisms are structured and whether or not they operate as a self-contained system, as in the sense of closed physical systems. Tansley (1935) was the first to formally define an ecosystem as a holistic concept of the plants, the animals associated with them, and all the physical and chemical components of the immediate environment, which together form a recognizable self-contained entity. As a self-contained entity, the ecosystem is governed by several processes that form the basis of CAS management. First, an ecosystem must have an input of energy that is equal to the demand of the organisms within it, as energy is harvested from the abiotic solar environment by photosynthetic organisms and flows through the biotic environment. Energy is used by organisms in metabolic processes and lost as heat at each transfer through the food web, resulting in pyramids of energy and biomass with photosynthetic organisms predominant at the base and carnivores at the pinnacle. Odum (1969), in his pioneering work on ecosystem ecology, used energy as the currency to define an ecosystem, stating simply that an ecosystem is an area within which the energy flow is in balance. It is important to note that this classic definition of the ecosystem was developed with the concept of an autochthonous system in mind, in other words, a system that is unaltered by humans from its natural state. In reality, most ecosystems today are strongly impacted by human activities and highly managed, such as agricultural systems. These highly managed systems are generally sustained by energy subsidies of various forms.

Another unique process at the ecosystem level of CAS is that nutrients and water cycle throughout the system by the processes of photosynthesis, respiration, ingestion, digestion, excretion, and decomposition. Pools of chemical elements such as carbon, nitrogen, and phosphorous exist in the atmosphere, lithosphere, and hydrosphere and are naturally released into the ecosystem through processes such as weathering and carbonation of rocks and minerals, microbial conversion of atmospheric nitrogen to ammonium, and uptake of atmospheric carbon dioxide by plants. Other nutrients may enter systems from the atmosphere, either by dissolving in rain as it falls to the earth or being deposited directly from the air. Once nutrients such as carbon, nitrogen, and phosphorous enter an ecosystem, they are repeatedly converted between organic and inorganic forms and recycled through the system. One important outcome of these processes of recycling and decomposition is the formation of soils, which serve as the foundation for productivity in both natural and agricultural and agroforestry systems.

Human activities now dominate the input and output of nutrients to many ecosystems around the world. Large quantities of carbon, nitrogen, and phosphorous are released into the environment as byproducts of industrial and agricultural practices, such as the burning of fossil fuels and use of nitrogen and phosphorous fertilizers. Globally, agricultural and forestry practices play a significant role in the disruption of natural nutrient cycles because continuous harvesting depletes nutrients in one area and transports them to another. Farmers and foresters who want to maintain long-term productivity must fertilize their lands with nutrients and other soil amendments to maintain high levels of productivity. If the system becomes unbalanced (e.g., too few or excessive nutrients), as is the case in many agricultural systems, external inputs (e.g., fertilizer) or export of excess nutrients (e.g., transport of excess animal manure and wastewater treatment plant residuals to nutrient deficient areas) may be required to maintain ecosystem integrity. These fundamental processes of energy flow, nutrient and water cycling, decomposition, and soil formation must inform the decisions made by planners at the ecosystem level and are key to maintaining balance in the lower levels of CAS, specifically watersheds, farms and fields. When imbalance is suspected, the manager must ask two questions to diagnose the imbalance and to recommend mitigation. How is the abiotic environment affecting the organisms within it? How are the organisms affecting the abiotic and biotic environment? Imbalance can come from one or both directions.

As the science of ecology has progressed, ecosystem science has been refined to clarify that human beings are an integral biotic component and have significant impacts on the biotic and abiotic components of most ecosystems. This was explicitly stated in the Millennium Ecosystem Assessment (MEA 2005a): Humans are an integral part of ecosystems. (The MEA, conducted between 2001 and 2005, included more than 1,300 experts around the globe working to evaluate the effects of ecosystem change on human wellbeing.) As addressed throughout this book, there is no shortage of examples of the myriad ways that the human species alters ecosystems. The challenge for managers of CAS is to identify what abiotic and biotic components are being affected and then to develop adaptive management strategies to restore energy flow and nutrient and water cycling in the system.

One of the major challenges for managers at the ecosystem level of CAS is defining the boundaries, temporally and spatially. As succinctly stated in the MEA, “Ecosystems vary enormously in size; a temporary pond in a tree hollow and an ocean basin can both be ecosystems” (MEA 2005a.) While defining the limits of a terrestrial-based ecosystem by barriers such as high mountains or deep rivers may be possible, marine and large-aquatic systems can be especially difficult to define for policymakers and managers. From an energetic perspective, an ecosystem may be defined as the area in which the demand of predators is equal to the production of prey. In terms of behavioral ecology, an ecosystem boundary may be defined to include the foraging range of the organisms that live within it, at least for a large part of their life cycle. Ciannelli et al. (2004) tried to address this question of defining ecosystem boundaries in a challenging marine system, the Pribilof Archipelago in the Southeast Bering Sea, an area of particular importance to multinational fisheries’ interests. They demonstrated that the foraging range of the breeding northern fur seals (*Callorhinus ursinus*), which are central-place foragers that depart from and return to a central breeding colony daily and are a dominant vertebrate species in this ecosystem, provided a good estimate of the ecosystem extent and the area needed to provide an energy balance in this oceanic system. Their work demonstrates that it is possible to draw boundaries on ecosystems that enable more coherent policy interventions.

For species with more complicated life histories, such as migratory salmon that spawn in inland streams and die after spawning while juveniles migrate back to the ocean to complete their life cycle, one may choose to define the entire area of their life cycle as one ecosystem or, more commonly, to refer to the inland waterways and ocean as different ecosystems used by these species at different stages of their life history. The challenge is for those in governance, policy, and markets to recognize that the ecosystem(s) required by a species of management concern, such as commercial fish species or migratory ungulates of Africa, may cover areas larger than a single national or regional government alone controls and thus require cross-border treaties or agreements for effective management (Valencia 1990; Smith et al. 2008; Sultanian and van Beukering 2008). In summary, the unique properties of the ecosystem level required by species of interest (because of economic, cultural, or biodiversity value) may serve as leverage for usually difficult negotiations between distinct scales of adaptive management.

Understanding what defines an ecosystem and its role as an organizing principle in ecology (as it encompasses the concepts of abiotic factors, organisms, populations, and communities) does not alone justify its importance as one of the highest levels of organization in CAS. The importance of the ecosystem level in the complex adaptive system paradigm comes from the fact that humans are but one of the many biotic components in an ecosystem and that humans stand to benefit from the properties and emergent effects of all the other abiotic and biotic components of these systems. These benefits are described as ecosystem services (MEA 2005a). The biotic and abiotic components, the process of water and nutrient cycling and energy flow, and the interaction of these abiotic and biotic components and the ecosystem processes create provisioning, regulating, and cultural services of extreme importance to human wellbeing at the field, farm, and watershed levels of the CAS. It is these ecosystem services, described in the following section, that are of primary interest to humans and markets.

Ecosystems: Features critical to the complex adaptive system paradigm

- Ecosystems are complex, and their unique processes operate at long-term and regional spatial scales.
- Energy flows through ecosystems while nutrients cycle within them. When energy or nutrients are out of balance, managers must identify the limiting factors and manage the system to alleviate the imbalance.
- Humans at the field, farm, and watershed levels of CAS cannot exist in the absence of the provisioning, regulating, and cultural services uniquely provided by ecosystems.

Ecosystem Services from Agricultural Landscapes

Agricultural lands provide a variety of ecosystem services. Ecosystem services have been classified in the Millennium Ecosystem Assessment (MEA 2005a) into four major groups: provisioning services (e.g., food, water, fiber/fuel), regulating services (e.g., air quality and water regulation, pollination, reduction of soil erosion and sedimentation), cultural services (e.g., spiritual values, aesthetic values), and supporting services (e.g., soil formation, nutrient cycling). In more recent formulations (e.g., Carpenter et al. 2006; Wallace 2007), the supporting services are now referred to as ecosystem processes rather than services, for their benefits to humans accrue indirectly only through subsequent links. Examples of services that are derived from agricultural land or are threatened by agricultural processes are detailed in the first two columns of table 1(a). As will be pointed out through various examples in this and other chapters, the effect of agricultural activities on ecosystem services, whether positive or negative, is not uniform across time and space. Understanding the scales at which services operate is essential to developing landscape-level management plans (Kremen 2005). Management decisions necessarily involve tradeoffs across services and between time periods (Foley et al. 2005; Farber et al. 2006). The International Assessment of Agricultural Science and Technology for Development described the need for improvements in delivery of science and technology information (Kiers et al. 2008). Environmental costs and unequal distribution of benefits in ecosystem service affect different players and levels in the CAS differently and may accrue immediately or over generations. Identifying the effects on ecosystem services of activities at multiple spatial and temporal scales is a critical step for planners and managers.

Ecosystem services

Three concepts are poorly understood by most people who are not familiar with ecosystem services:

- “Natural ecosystems provide services on which our economic, social, cultural, and political systems depend.
- “When these processes are altered, our quality of life declines.
- “When the processes fail, life becomes very difficult or impossible.

As a result [of this lack of understanding], … conservation is seen by many as a minor amenity benefiting a small cadre of birdwatchers or backpackers that stands in the way of ‘progress’ that benefits all” (Brussard and Tull 2007).

The benefit or cost in ecosystem services resulting from farming activities may accrue to the farmers primarily or entirely to people who have no physical or economic ties with the agricultural land. Farmers benefit directly from services such as pollination and on-farm cycling of waste products into soil nutrients. They may also benefit from increased food or medicinal sources if their farmland provides habitat for wild plant and animal species that the farmer harvests and consumes directly. However, the economic benefits of cultural services such as wildlife habitat provided by forest reserves, sacred groves, or fallow farmland that may be important to ecotourism or regulation of water quantity and quality tend to accrue to off-farm users, sometimes to people who live hundreds of kilometers downstream.

Understanding who benefits from a particular activity and how much different parties benefit is critical to effectively managing an ecosystem under the CAS paradigm. Different communities and cultural groups are likely to value ecosystem services differently. For instance, farming activities that result in soil erosion cause water quality problems primarily for downstream water users. Thus, in the absence of appropriate incentives, people who live downstream of their farms and rely on river water supply would be naturally more interested in investing in farming techniques that prevent soil erosion than those who live upstream of their farms. Similarly, some cultures have more concern for posterity than others. A society's propensity to utilize, degrade, or conserve intergenerational resources is a reflection of the discount it attaches to postponed costs and benefits (i.e., those that would accrue only to future generations). Women, who tend to bear responsibility for attending to sick family members, may place more importance than men on a close supply of medicinal plants (Howard 2003). Because the cultural, temporal, and spatial context will determine who benefits from a particular ecosystem service, the willingness of different communities or groups to conserve a resource will vary as well. Arnold Pacey (1983), in his book *Culture of Technology*, emphasizes the importance of addressing cultural values in development programs. By operating at the interface among technical, organizational, and cultural aspects, projects are more likely to accomplish the goals of a local community (Pacey 1983).

Evaluating Ecosystem Services in the Complex Adaptive System Decision-Making Framework: An Example

In addition to the real examples provided in this chapter to illustrate complexities in the decision-making process at the ecosystem level using the CAS framework, it is instructive to have a model system to visualize the idea of the complex adaptive system and to reinforce the notion of unequal distribution of the costs and benefits of ecosystem services related to agricultural practices. Figure 1 shows a small ecosystem defined by a river basin containing three subwatersheds in which watershed 1 and watershed 2 drain into watershed 3. The native vegetation in this model is tropical forest, but it could be wet or dry forest, with or without seasonality in temperature or rainfall. By using watersheds and subwatersheds to delineate the ecosystem boundary in this example, and generally at the higher levels of the complex adaptive system landscape, we are recognizing the importance of the hydrological regime as one of the major processes for delineating scales and boundaries of ecosystems (Noss 1996). Two villages are located in the ecosystem, called Highlanders and Lowlanders. The two villages are only 10 km apart, and citizens of these villages may own land in any part of the ecosystem. In the development of these models we used the following three assumptions:

- ***Model assumption 1.*** The three possible land uses in this ecosystem are natural forest, shifting cultivation in short rotations (less than 10 years) and without use of agrochemi-

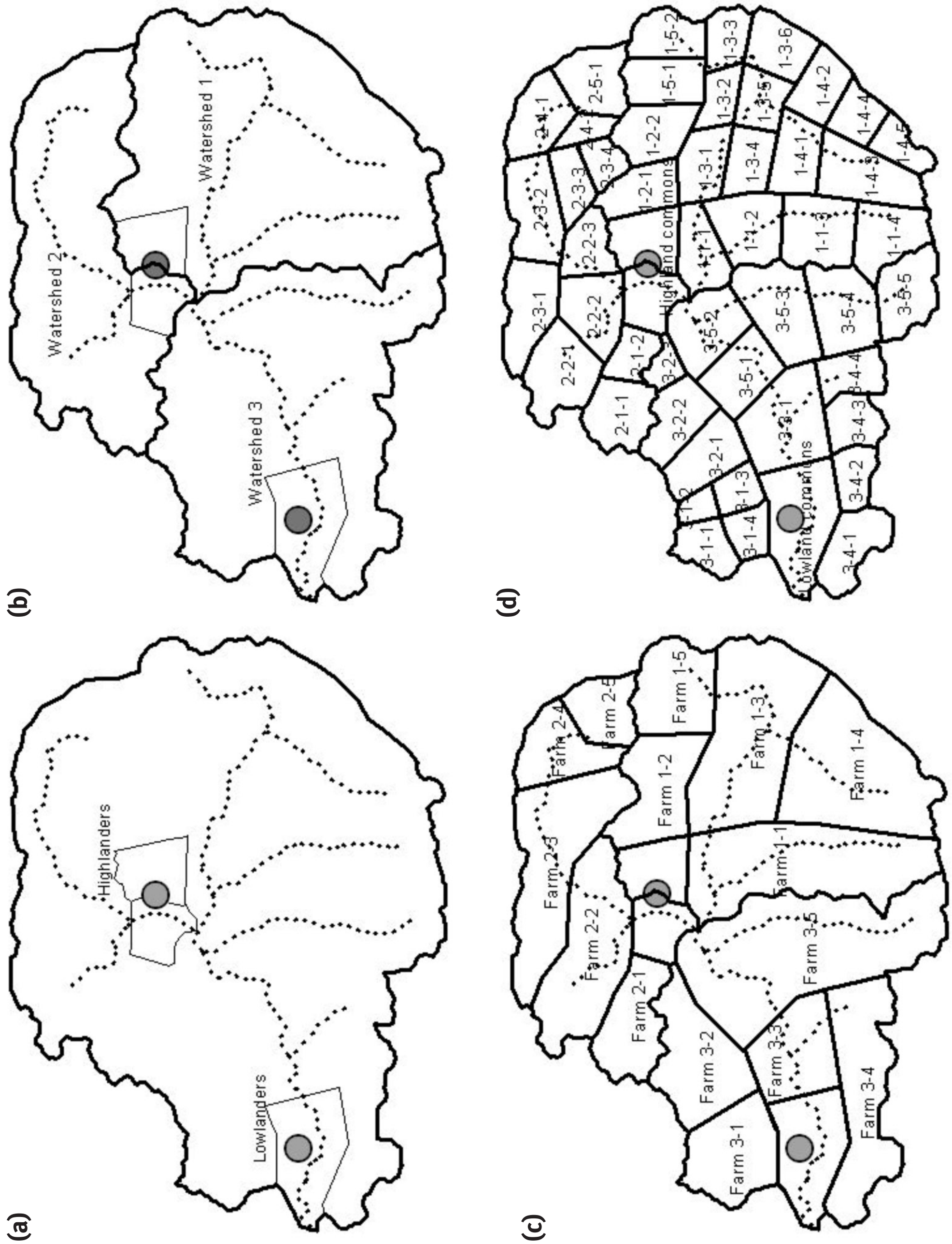

Figure 1. A model ecosystem shown sequentially (a) to (d), with two villages (Highlanders and Lowlanders), three watersheds (1-2-3), and hierarchically nested farms (farm 2-3 is farm 3 in watershed 2) and fields (field 2-3-2 is field 2 in farm 3 in watershed 2).

cals, and low intensity agroforestry without agrochemical use. By eliminating the use of agrochemicals (fertilizers), we are constraining the system to its natural nutrient cycling capabilities, which is typical in shifting cultivation and low intensity agroforestry systems. The main features defining shifting cultivation in this example are clearing of the field, burning of cleared vegetation in the field, growing crops, and abandoning the field for a new one in two to three years after soil fertility declines with successive crops (ThinkQuest 1999). We used short-rotation shifting cultivation to demonstrate an unsustainable system, although in some cases a farmer will not return to the abandoned field for 50 years or more (ThinkQuest), in which case soil fertility would return, woody vegetation will regrow, and shifting cultivation would represent a sustainable farming practice. However, in our example, the field is returned to cultivation when the fallow period has been too short to restore nutrients or regrow substantial woody vegetation.

In our model, we define agroforestry as the intentional co-planting of shade trees with agricultural crops (Bhagwat et al. 2008). The example agroforestry has extensive tree cover and diverse crops and, while structurally simpler, resembles the nearby forests in structure and function (Greenberg et al. 2008). We also presume that there is considerable homogeneity in the structure of agroforests across fields and the landscape, making their aggregated effect on the ecosystem more predictable. While functioning as farms, agroforests have the potential to provide wildlife habitat and serve as dispersal corridors connecting patches of natural forests (Bhagwat et al. 2008).

- ***Model assumption 2.*** In the long term, every field plot can change to another use, limited by what is feasible. For instance, it would not be possible for a field that was in short-rotation shifting cultivation for a long time to return to natural forest in the short term (e.g., less than 10 years). When farms contain some fields in short-rotation shifting cultivation, we presume that, in the long term, shifting cultivation will take over the entire farm, for degradation of the area managed through short rotations will force more intense farming activities to other areas of the farm. However, a farm that started out entirely in agroforestry could be maintained in the long term in agroforestry because this low-impact practice would continue to provide substantial benefits to the farmers. If a greater proportion of a farm/enterprise started in agroforestry or natural forest, any land in shifting cultivation would eventually be converted to a more sustainable practice as the long-term benefits become apparent. Forests will remain forest for a longer time, and some agroforest may rotate between secondary natural forest and agroforest over time.
- ***Model assumption 3.*** We purposely do not define the short, medium, and long time frames in terms of number of years but presume that the short time frame is equivalent to a few growing seasons and that the long time frame would occur over more than one generation.

Now consider the two land-use scenarios shown in figure 2. Tables 1(a) and 1(b) present ecosystem services that may be affected under these land-use scenarios (compared with the natural state of the watershed as tropical forest) and how these costs and benefits may accrue to the field, farm enterprise, watershed, and ecosystem under the two land-use scenarios. Note that the scale of service generation is not necessarily the same as the scale at which service accruing is being estimated. Freshwater supply and water purification, for example, are generated at the watershed and ecosystem scales, but the benefits of the services can be measured at any level in the CAS landscape. These tables focus on field 2-3-2, which is part of farm 2-3, which is in turn a part of watershed 2. The farmers of farm 2-3 live in the Highlanders village. Following the method of Farber et al. (2006), ecosystem services that are increased compared with native forest are indi-

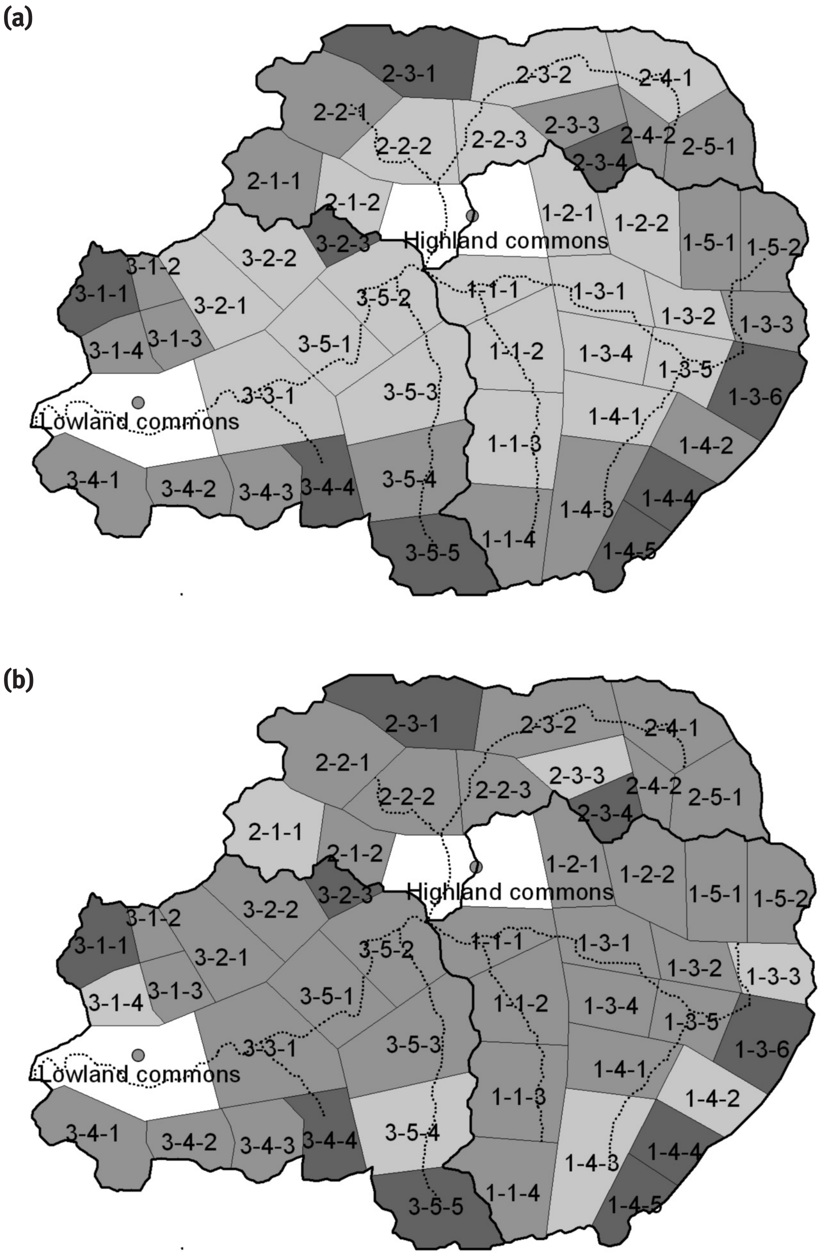

Figure 2. Alternative land-use scenarios in a model watershed (described in figure 1) with first scenario (a) depicting predominantly shifting cultivation near streams and in flood plains and agroforestry in highlands. The second scenario (b) depicts a watershed system dominated by agroforestry around streams and rivers. Dark gray = forest. Medium gray = agroforestry. Pale gray = shifting cultivation.

Table 1(a). Costs (-) and benefits (+) of ecosystem services related to the first land-use scenario depicted in Figure 2a: Owners of farm 2-3 live in the highland community and convert field 2-3-2 from natural forest to short-term shifting cultivation. Costs and benefits of ecosystem services are averaged for the stakeholders of the respective levels of the complex adaptive system landscape.

		Potential direction of change in service compared with natural ecosystem											
		Field 2-3-2			Farm enterprise 2-3			Watershed 2			Ecosystem		
Ecosystem service and category	Subcategory	Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term
Provisioning services													
Food	Domesticated crops, livestock	+3	+1	0	+2	+1	0	+1	+1	0	+1	+1	0
	Wild plant and animal food products	+3	-1	-3	+2	+2	-3	+1	+1	-3	+1	0	-3
Fiber/fuel	Timber	+3	-2	-3	+2	+1	-3	+1	0	-3	+1	-1	-3
	Wood fuel	+3	0	-3	+2	+1	-3	+1	0	-3	+1	0	-3
Biochemicals, natural medicines		-1	-2	-3	0	-1	-3	0	0	-3	-1	-2	-3
Fresh water		-1	-2	-3	-1	-2	-3	-1	-2	-3	-1	-2	-3
Regulating services													
Water regulation/ purification		-1	-2	-3	-1	-2	-3	-1	-2	-3	-1	-2	-3
Pest regulation		+2	-1	-3	0	0	-3	-1	-1	-3	-1	-1	-3
Pollination		+2	+1	-2	+1	0	-2	0	-1	-3	0	-1	-3
Cultural services													
Aesthetic values/ recreation and ecotourism		+1	-1	-3	+1	-1	-3	0	-1	-3	0	-1	-3
Sense of place/ cultural heritage values		+2	+1	-3	+2	-1	-3	0	+1	-3	0	-1	-3

Table 1(b). Ecosystem service accruals under second land-use scenario, depicted in figure 2b: Owners of farm 2-3 live in the highland community and convert field 2-3-2 from natural forest to agroforestry. Costs and benefits of ecosystem services are averaged for the stakeholders of the respective levels of the complex adaptive system landscape.

		Potential direction of change in service compared with natural ecosystem											
		Field 2-3-2			Farm enterprise 2-3			Watershed 2			Ecosystem		
Ecosystem service and category	Subcategory	Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term	Short-term	Medium-term	Long-term
Provisioning services													
Food	Domesticated crops, livestock	+1	+2	+3	+1	+2	+3	+2	+2	+3	+2	+2	+3
	Wild plant and animal food products	+1	0	0	0	0	0	0	0	0	0	0	0
Fiber/fuel	Timber	+1	0	-1	+1	+1	0	0	0	0	0	0	0
	Wood fuel	+2	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
Biochemicals, natural medicines		0	0	0	0	0	0	0	0	0	0	0	0
Fresh water		0	0	0	0	0	0	0	0	0	0	0	0
Regulating services													
Water regulation/ purification		0	0	0	0	0	0	0	0	0	0	0	0
Pest regulation		+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
Pollination		+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1
Cultural services													
Aesthetic values/ recreation and ecotourism		-1	-1	-1	+2	+2	+2	0	0	0	0	0	0
Sense of place/ cultural heritage values		+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1

cated with a +, those that are neutral with a 0, and those that are decreased are indicated with a -, and the magnitude of change is ordered from 1 to 3. The numbers allow us to assign relative degrees of change. For instance, +1 under food provisioning services would indicate a minor increase above levels in native forest, whereas a +3 would indicate a large increase. The numbers in tables 1(a) and 1(b) represent the average value for all nested components for the complex adaptive system level being studied. For the purpose of this model exercise, the "averaging" was done heuristically with no mathematical rigor enforced.

The first scenario shown in figure 2 has field 2-3-2 in short-rotation shifting cultivation. At the beginning of this cycle, field 2-3-2 is cleared from native forest. In table 1(a), we can see the effects at the field scale in the short term by reading down the first column at each level of the CAS. Clearing native forest allows the farmer to harvest a substantial amount of wood for timber and fuel in the initial year of the cycle. At the same time, wild game is readily harvested from the plot both before it is burned and later as animals enter from adjacent stands of mature forest. However, field 2-3-2 is located along a stream. The activities of field 2-3-2 together with nearby fields (2-2-2, 2-2-3, 2-4-1), which are also practicing shifting cultivation in riparian zones, results in diminished hydrologic services (water supply and quality) to the downstream Highlander village. As forest quality declines over time with increasing amounts of shifting cultivation, hydrologic services continue to decline. Pest regulation services would be high in the short term with the surrounding forests protecting the isolated field from crop pests. In addition, the surrounding forest would provide suitable habitat for many beneficial insects and birds that could serve as pollinators. A recent review found that avian pollinators increase in low-intensity agricultural fields compared with native forest and that bee populations remain constant (Tscharntke et al. 2008). The aesthetic and recreational values of a cultivated field would decline relative to native forest, but the cultural values and sense of place might increase as farmers began to make their mark on the land and successfully grew crops to provide for their families.

The changing costs and benefits of ecosystem services in the medium and long term of this example are shown in columns 2 and 3 of each CAS level in tables 1(a) and 1(b). As the amount of forest declines, less timber and fuel wood are available, and more weedy vegetation begins to invade the fields. The insufficient fallow period results in more water runoff and the loss of topsoil and nutrients. Siltation of streams and rivers increases with the increase in shifting cultivation, and as more of the land shifts from late- or mid-succession to early-successional habitats, pollination services and pest regulation services decline. Once the fields become highly eroded and unproductive, there is little value for food production and no longer the benefit of pride in place or cultural heritage values.

As our focus shifts in spatial scale to the farm enterprise level (shown in columns 4 to 6 of table 1[a]), the patterns are similar to that at the field level, although because farm 2-3 incorporates a substantial amount of native forest and a small stand in agroforestry, more of the benefits of shifting cultivation persist into the midterm, while the overall farm is still relatively diverse. In the long term, however, the shifting cultivation spreads from the now-depleted fields into the native forest, causing an ultimate collapse. At the watershed and ecosystem levels (shown in columns 7 to 12 of table 1[a]), because many fields are in shifting cultivation, especially those that border stream corridors, there are fewer benefits even in the short term, and the decline in services happens faster at these larger scales.

The second scenario (figure 2, table 1[b]) shows a contrasting situation in which many of the farms start out with low-intensity agroforestry and no shifting cultivation. Based on model assumption 2, we expect shifting cultivation to remain limited or to change to agroforestry in the long term, with agroforestry fields remaining in agroforestry or transitioning between agroforestry and natural forest. While provisioning services may not accrue initially in quantities as high as the first scenario, these services are sustained over time. Most services are still provided at levels greater than or equal to that obtained from the natural forest, as indicated by the 0s, and services are rarely generated below natural levels. At the watershed and ecosystem levels, because almost all of the land surrounding stream corridors is native forest or agroforestry, high-value hydrologic provisioning and regulating services are provided. The long-term outcomes at these higher scales allow for a variety of sustainable ecosystem services. While there is greater individual immediate benefit in the form of most provisioning services in the first scenario, these are accompanied by shared societal costs in the form of diminishing regulating and cultural services, especially in the medium and long term. These regulating and cultural services mostly fall in the purview of common property and public goods, the preservation of which is often ignored or even subconsciously sabotaged by individual-level decision making (Hardin 1968; Odum 1982). In the second scenario, individual gains are not at the expense of large-scale and long-term deterioration in ecosystem services. Hein et al. (2006) analyzed the ecological scales (plant-plot, ecosystem) at which ecosystem services (provisioning of reed and fish, recreation, nature conservation) are generated and the institutional scales (individual, family, municipal, state/provincial, national, international) at which services accrue to stakeholders from a wetland. Not unlike CAS expectations, they concluded that stakeholders at different scales can have very different interests in ecosystem services, emphasizing that the consideration of scales is crucial in the formulation or implementation of management plans.

The previous scenarios are simplifications for illustrative purposes. For instance, there may be biophysical constraints (perhaps soil fertility is much higher in the floodplain, or upland slopes are too steep to permit cultivation) to the location of certain agricultural or land-use practices in the landscape. Two important inputs for projecting the trajectories of future land uses are past land-use transitions in the landscape (formally, a transition probability matrix) incorporating biophysical constraints, and the specific market and policy context (such as existence of credit, incentives, or technical support for adopting alternative practices) that are expected to influence current and future decisions.

Different individuals may make different decisions when presented with the same biophysical and market conditions. For example, the tendency of a farmer to adopt a particular practice may be a function of level of education (Abdulai and Binder 2006) among other socioeconomic factors. There is general supporting (Abdulai and Binder 2006) and contrary (Borggaard et al. 2003) evidence for increased use of chemical fertilizer as a consequence of short-rotation, slash-and-burn shifting cultivation. Fertilizers increase productivity by reducing nutrient losses from intensive cropping and erosion. When credit is available, farmers may purchase more inputs to improve productivity (Abdulai and Binder 2006). In the absence of credit, the cost of fertilization is prohibitive for subsistence farmers, who tend to compensate for declining production by increasing labor instead (Borggaard et al. 2003; Abdulai and Binder 2006).

A scenario that involves extensive use of fertilizer in shifting cultivation would present its own suite of new challenges in the CAS. Besides the upfront cost to farmers or to governments in the form of subsidies, efficient fertilizer-based shifting cultivation would require a different cropping system than the typical agro-diverse farms. In subsistence farming, fields are often planted to multiple crops, but different crops have different nutrient requirements. Fertilizing all with the same fertilizer will not be so effective, but there are cash and labor costs of trying to apply different chemical fertilizers on the same field. If fertilizer use encourages reduction of crop diversity, this has negative implications such as increased risk of disease, pests, crop failure, and dietary deficiencies; and increased plant-plant competition from reduced variation in plant architecture, water, and nutrient demands. External costs of intensive fertilizer use in shifting cultivation include water-quality problems from non-point source nitrogen and phosphorus exported to streams. Our analysis of costs and benefits at the hierarchical scales did not go beyond boundaries of the single ecosystem. However, it is convenient here to point out that investment in fertilizer may not accrue benefits to the local market, for fertilizers are typically imported. Purchasing non-local inputs has implications for other ecosystems in ways that our model is not designed to address (e.g., implications for global carbon budgets).

Clearly, the many factors that affect decisions and consequently projection of alternative futures for the CAS tend to be context-specific. However, as an illustration of decision making at the ecosystem level using the CAS framework, we hope the process is clarified and that users and decision makers can envision with this simple example what it would take to create realistic alternative futures to guide their decisions. In the following sections, we provide a variety of examples of real-life management dilemmas and solutions. We hope this example may serve as a template for understanding these real-life scenarios.

Managing for Ecosystem Services on the Ground: Examples from Real Complex Adaptive Systems

To ensure that appropriate incentives are in place to achieve environmental goals, practices that provide direct benefits to farmers without substantial cost to the larger society should be used. Alternatively, there should be financial incentives for farmers to provide such services to others. In some systems, penalties rather than rewards are used to encourage agricultural practices that reduce damage to ecosystem services. However, this approach often requires a significant infrastructure for enforcement of penalties, which often may not be feasible.

Development of sustainable and environmentally sound agricultural production systems requires multidisciplinary teams with knowledge of agricultural, cultural, economic, and ecological systems. A multidisciplinary approach allows solutions to be identified for what may seem like intractable problems. For example, grassland songbirds have shown serious declines across much of North America (Askins et al. 2007) and Europe (Krebs et al. 1999; Vickery et al. 2004). Many native prairie species now breed primarily in hayfields. When hayfields are mowed in the spring, bird nests are destroyed, and there is often complete reproductive failure for these species. Conservation biologists had hoped that farmers who had learned about the condition of the birds would delay mowing until after peak breeding season, but this did not occur. The problem was not that farmers did not care about grassland birds but that the conservation biologists failed to recognize the real economic costs of delaying haymaking. The forage value of a hay crop peaks at a particular time of year. For alfalfa, that point occurs just as the plant is beginning to flower. For most grass species, that point occurs before the plant sends up a flowering stalk. Cool-season grasses should be cut in early spring and, depending on environmental conditions, can often receive a second or third cutting before growth slows. If farmers delayed cutting a cool-season grass hay until mid- to late summer, the nutritional value and palatability to livestock would be severely reduced to the point that they might lose money cutting and baling it. Understanding this constraint on the farmers' part makes clear that asking a farmer simply to delay cutting hay is not a viable option for saving the birds.

But is there no way that we can expect farmers to provide suitable nesting habitat for grassland birds? In fact, such a solution exists and is being implemented across many small landholdings in rural North America. Cool-season grasses have been planted extensively in the southeastern United States because they green up early and provide needed forage after the winter. However, they grow little if at all in the heat of the summer. During hot, dry summers, many farmers must begin feeding hay in August because pasture forage is depleted. Feeding hay is expensive compared with grazing, and there is always a risk of not having enough hay for the winter. By moving livestock onto warm-season pasture, farmers can rest cool-season fields, allowing them to stockpile forage. Using this system, it is sometimes possible to delay feeding hay until November or December. The songbirds can use the warm-season pastures, and more cool-season hayfields may be converted to pastures in which birds also have higher breeding success. Converting some pastures and/or hayfields to native warm-season grasses can provide important benefits to both farmers and grassland birds. Policy incentives have been developed to facilitate these practices, and similar strategies may be applicable in other countries.

Other practices that may provide little or no benefit to farmers but important ecosystem services to others may require direct financial compensation for adoption by land users. Some examples of payment for ecosystem services include park revenues being used to assist communities maintaining adjacent buffer zones (Budhathoki, 2004) and water charges or tariffs being used to conserve forest cover, thus maintaining hydrological regimes, in important watersheds (Pagiola et al. 2004). Some nongovernmental organizations have also provided payments to conserve biodiversity through conservation concessions that compete with logging concessions or other economic activities by leasing rights to manage land (Hardner and Rice 2002). An important component of this practice is to avoid the creation of "perverse incentives." For example, if farmers can be paid for planting trees with no other constraints, they may cut down native forest so they have a place in which to plant trees (Pagiola et al. 2004). A better incentive would be to pay farmers annually to maintain native forest and to pay a lesser amount for planting trees on degraded lands.

Examples of ecosystem services that may have benefits to both farmers and off-farm members of the community are probably the most common. These cross-scale interactions and linkages, when made visible to and valued by all stakeholders, are what can help to bring about successful natural resource management on agricultural lands at the ecosystem level. In the following three examples, we focus first at the field and farm enterprise scale, then at the watershed scale, and finally at the ecosystem scale, although we consider effects for each at all scales.

Field/Farm Enterprise Scale: Soil Fertility, Waste Disposal, and On-Farm Recycling Services

As discussed in chapter 2, increased soil organic matter brings multiple benefits such as increased water-holding capacity, soil microorganisms, and availability of nutrients. In some parts of the world, there is a clear link between health of soils and health of the local people (Sanchez and Swaminathan 2005). Management practices that retain and recycle as much organic material (crop residue, manure, post-consumer food waste) on the farm as possible are better able to maintain or improve soil quality. (See chapter 2 for more information.) Despite the importance of good soil management, loss of nutrients and high soil erosion rates are a growing problem globally, and desertification—the process of degradation of soils to the point that they can no longer support plant life—affects 20 million to 32 million square kilometers of land worldwide (Stringer 2008). These are instances in which nutrient cycles need to be restored. The use of composted night soil (human excrement) in fields in developing countries is a valuable way to return nutrients and organic matter to the soil (King 1911) that is paralleled today in industrialized countries when sewage sludge is applied to fields. However, safety measures are important to reduce the risk of disease transmission or spread of anthropogenic contaminants. When farmers fail to use crop residues or livestock manure on fields, it is usually because these resources are diverted for use as fodder, fuel, or building materials. In this case, creating a more diverse cropping system is essential. A fast-growing leguminous cover crop can be planted as a green manure and incorporated into the ground after food crops are harvested. Establishing a woody field border managed as a coppice (continuous harvest and regrowth) system can provide a source of fuel wood and provide more diverse habitat for wildlife, including pollinators and predators of crop pests. Then not only can crop residues and livestock manure be applied to the fields rather than burned as fuel, but tree leaves can be used as fodder or to increase soil organic matter. An additional nutrient benefit would be available if nitrogen-fixing plant species were used. Leguminous tree fallows have been successfully used in eastern, western, and southern Africa to restore soil fertility. They are planted with a crop such as maize during the rainy season. After the maize is harvested, the trees continue to grow through the dry season, their long roots utilizing deeper soil water. The field is kept in tree fallow through the next dry season, when the fuel wood is harvested and leaves and remaining vegetation incorporated into the soil before planting the next maize crop, contributing 100 to 200 kg of nitrogen per hectare over a half-year to two-year period. On subsequent mineralization, the added nitrogen may double or quadruple maize yields over the next one to three growing seasons (Sanchez and Jama 2002; Sanchez and Swaminathan 2005). Where subsoil is extremely low in nutrients, use of woody vegetation for alley cropping or in rotations is unlikely to be able to add nutrients to surface soil. In these cases external fertilizer sources may be very important to improving productivity if the soils are able to hold nutrients long enough for plant uptake to occur (Lal 1989).

In addition to the important benefits on the farm, good soil and nutrient management helps to maintain water quality by reducing sedimentation and eutrophication. A major problem with industrial agriculture is nutrient imbalance. This also occurs commonly when smallholders specialize in one or a few products and/or when consumers of agricultural goods are distant from producers. Any field from which a crop is harvested repeatedly will lose nutrients. Any livestock provided with feed rather than grazing will concentrate nutrients (through manure and urine) in the areas where they are fed, potentially degrading water quality (Gerber and Menzi 2006). Sustainable agricultural practices balance nutrient loads by integrating livestock and crop production and/or by recycling waste onto fields. Diverse operations that rotate or combine production of livestock and diverse grain and vegetable crops on the same plot of land or in close proximity can simultaneously maintain soil fertility and address waste disposal needs (Gliessman 2007). Farmers benefit from sustained soil quality, and downstream users of water benefit from a cleaner water source. Focusing on the ecological principle of balance between inputs and outputs can help identify unsustainable systems that are vulnerable to collapse and negative off-site impacts. Farming operations that resemble natural systems by maximizing use of internal or local inputs are most likely to function sustainably.

Watershed Scale: Clean, Reliable Water and Water Sources

The dominant land cover has a major effect on provisioning of clean and reliable water. In general, when rainfall can infiltrate slowly into soils it is stored and is available over a longer period. This occurs, for instance, when rain falls on a forest canopy or on densely vegetated grassland. When rain falls on bare soil or packed or paved surfaces, much of it runs off (often carrying soil with it), causing flash flooding followed by periods of low water availability, for without water percolation through the soil and groundwater storage, there is reduced flow to rivers and streams in between precipitation events. The spatial arrangement of land-use types in a watershed has important implications as well. Crop fields separated from streams by a grassy or forested buffer are much less likely to contribute to sediment and nutrient loads in streams than fields cultivated right up to the water's edge. Important benefits accrue to native biodiversity (including some species that may be part of commercially important fisheries) as well because many aquatic species benefit from shade and inputs of woody debris and decline under increased sedimentation or eutrophication. Eutrophication, from the Greek "well nourished," describes the change in a water body in response to increased nutrients. Although in certain conditions the addition of nutrients can benefit fisheries, eutrophication is usually associated with a decline in water quality and aquatic resources. See the last paragraph in this watershed section for a discussion of anoxic or "dead" zones that can result from eutrophication.

Downstream effects of forest clearing

An example of how land-use practices at the field scale can have watershed-level effects was driven home to one of the authors on a trip to the Philippines in the early 1990s. At the Davao City airport on the southern island of Mindanao, there was no power to operate conveyor belts and other electrical equipment. The city had been suffering from frequent brown-outs despite substantial investments in hydroelectric power. Power generation requires sufficient flow of clear water to turn the turbines. Forest cover had been lost rapidly in the watershed through a combination of logging concessions and an influx of slash-and-burn farmers who gained access along logging roads. Soil loss rates from crop cultivation on the steep slopes of Mindanao have been known to exceed 340 to 400 t/ha/year (Proud 2004) (400 t/ha/year $\approx$ 2.5 cm depth of soil lost per year). The combination of deforestation and field cultivation caused severe siltation of the reservoirs, diminishing their power-generating capabilities and requiring more frequent repair or replacement of equipment than anticipated (Banos 2006). In addition, rivers that formerly had substantial flow rates through the year now showed the extreme high and low flows typical of deforested watersheds. As Proud (2004) pointed out, the economic value to the mountain farmers of the corn and cassava that were produced was minuscule compared with the societal costs of reduced electric power, flood damage, crop failure, and less reliable water supply in the lowlands. No rational planner would have encouraged these tradeoffs, but to a farmer in the highlands trying to feed a family, the decision to till highly erodible soil on hillsides with greater than 50% slope seemed reasonable without other available options. Similar to the tragedy of the commons (Harding 1968), the "tyranny of small decisions" (Odum 1982) can have far-reaching societal effects.

Managing water has important on-farm implications as well. In areas with limited rainfall during the growing season, various practices are used, some of which have a long history. Irrigation is an obvious solution, but it requires significant initial and continued investments, can result in salinization of soils, often competes with other water users (such as downstream industry, urban, and rural residents), may negatively affect native plant and animal life, may result in increased pest and disease problems, and may also result in local climatic changes (Gliessman 2007; Molden et al. 2007). Consideration of the potential negative impacts of irrigation is essential, and many systems still cannot be sustainably irrigated (Gliessman 2007; Molden 2007; Molden et al. 2007). An alternative to irrigated farming in semiarid regions is "dryland farming" and involves summer fallows or rest seasons that allow soil moisture to build up by reducing evapotranspiration (Gliessman 2007). Cultivation of the surface during the growing season removes weeds, allows moisture to penetrate, and can create a "dust mulch" to reduce evaporation. This system was used historically on small farms in China (King 1911), where farmers would plant in alternate plots over time. It is commonly used today in major grain-producing areas of the United States and Canada, and is used in Australia in a grain-pasture rotation (Gliessman 2007). Although this system makes very effective use of limited precipitation, there is an increased risk of soil erosion during the fallow period, and it may require cultivating more acres because crops can be produced only every other year. It is certainly not appropriate to use on marginal soils that are damaged by cultivation of any kind. Other techniques that may be used include building structures for harvesting seasonal rainfall (Bruins et al. 1986; Gliessman 2007, chapter 6) or planting woody shelterbelts that can provide shade, draw water up from deeper levels using tree species that may have deep taproots, and capture blowing snow in regions with significant precipitation as snowfall.

A more suitable option for semiarid and other tropical areas may be conservation tillage systems in which crop residues are maintained on the soil surface after harvest and planting to provide a mulch cover, which protects the soil from erosion and enhances infiltration. Maintaining plant residues on the soil surface can be a challenge due to foraging livestock and wildlife, but it has been shown to increase soil quality in terms of organic matter, structure, water-holding capacity, and fertility. If managed correctly (adequate weed control), it can increase yields within two to five years (National Research Council 2008).

In many arid and semiarid regions, the most sustainable use of the land for agriculture may be for grazing livestock. Grasslands and savannas provide important ecosystem services (including better carbon storage than some forests and supporting many threatened and declining species), but because of ease of conversion and cultural perceptions they may be destroyed faster than forests (Samson and Knopf 1994). The Millennium Ecosystem Assessment has documented that globally, more than 70% of the world's natural grasslands had been lost by 1950 and that another 15% was lost between 1950 and 2000 (MEA 2005b). Grasslands or shrublands that evolved with large native herbivores are more likely to be able to sustain grazing from introduced livestock such as cattle, sheep, or goats. When properly managed, livestock can often sustainably graze native vegetation and may improve soils and vegetation diversity (e.g., Reid and Ellis 1995). Following the principle of mimicking natural disturbance patterns, grazing practices like those of native grazers are likely to function well in a system. For instance, management-intensive rotational grazing practices common in much of North America are thought to mimic a herd of bison that puts intense pressure on a pasture for a short period of time before moving on. This "holistic resource management" was developed in Africa to restore degraded lands by concentrating livestock in small areas for brief periods of time (similar to native herding animals) to stimulate plant growth and provide enough soil surface disturbance to encourage seedling establishment and water infiltration (Savory and Butterfield 1999).

In times of scarcity or drought, farmers are often pushed to overgraze, to cultivate marginal land, or to remove woody vegetation. This can quickly lead to a long-term decline in productivity through loss of topsoil and can have regional consequences through dust storms, changing albedo, and shifting precipitation patterns (Smith 1953; Asner et al. 2004; DeFries and Bounoua 2004; Sampaio et al. 2007). It is important for governments to get involved in planning for droughts and having enforceable agreements that provide for livestock forage but prevent grazing of marginal lands that would be easily degraded. For instance, grass-banking can be used to provide dry-season or drought-year reserves (Neely and Hatfield 2007). During the time that they are not being grazed, these fields provide valuable wildlife habitat.

In areas with adequate rainfall, on-farm water and nutrient management still has important consequences both on and off the farm. Erosion can cause long-term declines of productivity. Flushing of nutrients downstream from excessive nutrients applied on farms can contribute to eutrophication and resulting oxygen depletion and "dead zones" in distant water bodies. These dead zones are formed when excessive nutrients cause algal blooms or rapid growth of other aquatic plants. When these plants die and decay, decomposing bacteria consume so much oxygen that the oxygen in surrounding waters is depleted. Fish must move elsewhere, and organisms that cannot disperse, such as shellfish, die from the lack of oxygen, adding to the oxygen demand problem. Such dead zones can affect large areas and result in massive losses of productivity from aquatic habitats, affecting availability of protein sources for local diets and of important commercial products. Diaz and Rosenberg (2008) report that dead zones are growing exponentially around the world, and there are now more than 400 such zones covering 245,000 km^2. Following the principle of thinking at multiple scales, there could be clear benefits to downstream users to create incentives for upstream farmers to better manage nutrient runoff from their fields (Pagiola et al. 2004). In response to a growing hypoxic zone in the Gulf of Mexico, the Land Stewardship Project started a training and monitoring project for farmers interested in holistic management (Jackson 2002; DeVore 2002).

Ecosystem Scale: Maintaining Native Biodiversity through Dominant Vegetation

Preserving native biodiversity in and around agricultural fields has benefits to both farmers and the surrounding community. Farmers benefit from pollination and pest control services provided by many native species (see textbox below). The larger community may benefit from the same services, from increased ecotourism opportunities, and from the intrinsic cultural and aesthetic values of species conservation. In areas where hunting and fishing occur sustainably, native fish and wildlife can provide an important protein source.

Pest control by native wildlife

Recent studies have documented the importance of bat populations in controlling arthropod densities. By creating mesh structures that were installed only by day or only by night, researchers were able to exclude bats alone, birds alone, or birds and bats from foraging on or around certain plants. In Mexican coffee agroforest during the wet season, arthropod densities were 84% higher in bat-only exclosures than on control plots (Williams-Guillén et al. 2008). A similar study conducted in Panamanian tropical lowland forest demonstrated that arthropod density was 153% higher on plants in the bat-only exclosures compared with control plants and twice as much leaf area was lost to herbivory (Kalka et al. 2008). In both systems, birds also played important roles. By protecting populations of native birds and bats, farmers may gain valuable services in controlling populations of leaf-eating insects.

Because of increasing prices of food and biofuels, and because of expanding human populations, there is pressure to convert more natural habitats to agriculture, although around the globe much of the most productive land is already farmed (Rights and Resources Initiative 2008). Land conversion usually has negative effects on native biodiversity and many ecosystem services provided by the natural habitats (see tables 1[a] and 1[b]). Because most of the land remaining to be converted has only marginal value for agriculture, it may be productive for only a short time or not at all, resulting in a financial loss for those who made the effort to convert it. Agricultural practices that are compatible with or resemble in structure the dominant native vegetation will require the fewest external inputs to implement and maintain. They may have the highest likelihood of success because they are compatible with natural patterns of rainfall, disturbance, and fertility. They also may be most likely to maintain native biodiversity and to provide ecosystem services similar to those of the native vegetation. However, such systems require the farmer to have an intimate knowledge of the land and the different crop and wild species involved. Such knowledge is often lost when communities are displaced or when farming is not passed through generations (Brush 2004). Humans can obtain resources in a semiarid prairie or savanna historically grazed by native ungulates as part of a functioning native ecosystem by harvesting wild ungulates for protein and harvesting native plants as a food or medicinal source. Grazing domestic livestock in such a system would retain the native plant cover and possibly much of the native wildlife but allow more control. Tilling the soil would be much more disruptive; however, if crops were to be planted, grain crops that were similar to the native grasses might better survive with natural precipitation than alternative crops. A polyculture (e.g., multiple species growing in the same field) is likely to produce more annual net primary productivity than a monoculture, thus more harvestable biomass (Flombaum and Sala 2008). A polyculture will also provide habitat to support a greater diversity of native animals.

Even if agricultural practices must differ drastically from the structure and disturbance regime of the dominant native vegetation, providing buffers or corridors of native or semi-native vegetation around or through the crop fields can provide many benefits in the form of ecosystem services. (See the following section on landscape level issues, dispersal corridors, and riparian buffers.) Vegetative buffers have been adopted to reduce erosion on steep slopes (Cramb and Culasero 2003; Gliessman 2007). Wider buffer zones around crops can support a higher plant diversity (Ma et al. 2002) and higher ratios of predatory to herbivorous insects (Denys and Tscharntke 2002). When buffer zones or corridors of native vegetation provide direct as well as indirect economic benefits (e.g., as sources of medicinal plants, fruit or nut crops, edible greens, or fuel wood and timber), they will be more likely to be incorporated and maintained in agricultural landscapes (Current et al. 1995).

Ecosystem-Level Forest Management in Complex Adaptive Systems

Value of Natural Forest Cover

In areas with natural forest cover, maintaining as much forest cover as possible is likely to have benefits to both local producers and the larger society. Forests provide many important ecosystem services such as water regulation (flood control) and purification, soil retention, climate modulation, carbon sequestration, material for timber and fuel, biodiversity protection, and cultural services. Retaining old-growth forest reserves can have important benefits, including maintenance of intact soil fauna, habitat for old-growth dependent wildlife, carbon and other nutrient storage, as well as disease reduction (Foley et al. 2007). Communities that live close to native forest stands may appreciate these as religious sites and will have access to native plants that may have important food, cultural, or medicinal value, and access to native wildlife that can serve as a protein source (Bhagwat and Rutte 2006). In fact, such ecosystem services appear to attract human settlement near protected reserves (Wittemyer et al. 2008). Forests may be managed for the production of timber and wood fiber as well as for non-timber forest products such as rattan and medicines (MEA 2005b, 2005c). Extraction of nonwood forest products may have great importance to local people and is usually of most importance to those in greatest poverty (MEA 2005c). One of these forest products, "bushmeat," has received attention from conservation groups. There is certainly a risk of driving some wildlife species into severe declines through overharvesting, primarily when roads provide access from urban to remote areas and market hunting increases (Robinson et al. 1999; Brashares et al. 2004). Loss of species that play a keystone role in the system, such as fruit bats that serve as major seed dispersers, could have severe negative consequences. Likewise, certain species may have higher value in certain cultural roles or through ecotourism than as harvested game. However, sustainable harvesting of wild game for local use (not usually as a commercial enterprise) has been practiced historically around the globe, and under certain circumstances it can be highly sustainable (e.g., Berkes 1999; Pei 1999; see textbox below). Partnerships among local communities, scientists who can provide larger scale information, and government organizations can produce effective management schemes (e.g., Lewis 1995).

Sustainable hunting practices and ecosystem management

The key to responsible harvesting of wildlife is to harvest only a sustainable yield (Caughley and Sinclair 1994). This yield can be described as the rate of increase in the population. Working with a trained wildlife biologist is critical to designing a sustainable harvest. Wildlife biologists refer to additive and compensatory mortality. Additive sources of mortality are those that will accrue in a population regardless of other sources of mortality. For instance, the number of deer in a population that are killed in vehicle collisions would probably be the same whether some animals were also killed by hunters in that area or not. Being hit by a vehicle and being killed by a hunter are considered additive sources of mortality. In contrast, the number of deer that starve to death during the dry season would likely be reduced if hunters killed a lot of deer the previous season. Food outside the growing season can be a limiting resource for deer, and if fewer deer are competing for it, each of them is more likely to get enough food to survive, so the incidence of starvation declines. Hunting is then considered to be a compensatory form of mortality because the post dry-season population size is likely to be the same whether animals were hunted or not. (In unhunted populations more animals starve, while in hunted populations fewer animals starve.) When hunting mortality is compensatory in relation to other major forms of mortality, it is relatively easy to harvest animals sustainably, that is, without reducing the standing crop of livestock. Animals with short life spans and high reproductive rates can usually be harvested sustainably. In contrast, animals that are long-lived require many years until they are old enough to reproduce, and generally produce only a few young each year can be very difficult to manage through sustainable harvests. When harvests target individuals that have low reproductive value, the effect of harvest on the population is reduced (Gotelli 1995). For example, the reticulated python (*Python reticulatus*) is harvested in Sumatra for the commercial leather industry. Although harvest of several temperate zone snakes has been shown to be unsustainable, the python population appears to have been able to persist despite large removals. This species has rapid growth, early maturation, and high fecundity (mean clutch size of 24, produced every two to four years). Large females produce the largest number of young and reproduce most frequently. An important factor in the sustainability of this harvest may be that large females were rarely harvested, probably because they prey on large native mammals in mature forest and thus avoid disturbed areas where humans most often collect snakes (harvesting smaller individuals that eat rats and mice around houses and fields). The combination of several factors has contributed to the sustainability of this harvesting system (Shine et al. 1999).

Old-growth stands may remain on the landscape for cultural or religious reasons, or because the topography is too steep or access is otherwise limited. When new technologies such as helicopter logging become available or access is increased through road construction, when population pressures require an expansion of land in cultivation, or when immigrants arrive who do not share cultural or religious practices, these old-growth forest stands are at risk (Bhagwat and Rutte 2006). Costs and benefits of forest conversion should be carefully weighed at a landscape and long-term scale, and policies and infrastructure should be designed to achieve societal goals for retention of forest cover and management of existing old-growth stands (Carvalho et al. 2001; Soares-Filho et al. 2004).

Landscape-Level Issues, Dispersal Corridors, and Riparian Buffers

The spatial distribution of forest openings has a major effect on many ecosystem processes and services. For instance, clearing native vegetation may change local rainfall patterns (Turner and Chapin 2005; Chapin et al. 2008). Human communities may benefit from retaining forest reserves, and these function best when surrounded by at least a partially wooded landscape. (Even when isolated, old-growth patches or even individual trees can provide important benefits, such as trees in Costa Rican pastures that support forest wildlife [Harvey and Haber 1999] and can help natural reforestation of abandoned pastures). The ability of remnant forest patches to support native biodiversity varies with the proportion of the landscape that remains in forest cover, the size of the patches, their distance from larger forests, and the connectedness between patches or the contrast between forest and surrounding land-use types (Robinson et al. 1995; Willson 2004; Newmark 2008). The amount and distribution of forest cover is also important in protecting freshwater systems (Saunders et al. 2002).

The term silviculture describes the long-term management of forests for production of trees as well as other objectives. Unlike silviculture, logging can be conducted without regard for long-term productivity of a forest (e.g., Grogan et al. 2008). Logging activities in areas that are planned to regenerate as forest should be designed and supervised by a trained silviculturalist with local knowledge. Although unsustainable timber harvest practices have caused severe environmental problems, well planned and executed management practices allow for sustainable harvest of wood products in many systems (Freer-Smith and Carnus 2008; Meijaard and Sheil 2008). Sustainable forestry practices could help maintain forests on the landscape while providing an income to local residents. Compared with most agricultural crops, trees grow on a much longer time scale. Because the benefits of sound silvicultural practices may occur primarily to future users, balancing current with future costs and benefits is challenging. Harris (1984) described a simple scheme for retaining old growth forest reserves while harvesting timber. Circular forest reserves are surrounded by managed forests, creating an important buffer between the forest reserve and agricultural fields and residential developments. The doughnut-shaped managed forest is then divided into wedges, and wedges are harvested in a determined order (figure 3). If wedges are harvested sequentially, each wedge would have at least one border with a similarly aged forest patch, reducing fragmentation and edge effects. Much of the managed forest would always be in a relatively mature state. The central reserve could provide a ready source for colonization to all the wedges, providing a seed source and pollination services as well as maintaining wildlife populations.

When permitting logging or mining concessions, it is important to consider future scenarios that include large-scale effects of many local decisions and that balance needs of different stakeholders (Jackson et al. 2007). For example, much of the western Amazon basin is currently remote and relatively undisturbed. It contains high levels of biodiversity, several uncontacted cultures, and is considered to be an important area for maintaining carbon stores. Current and proposed oil and gas drilling leases, however, would require that roads be built through much of this area. Once roads are built, the opportunity costs for timbering, market hunting, and farming are reduced, and these activities typically spread rapidly across the landscape. The distribution of all of these leased

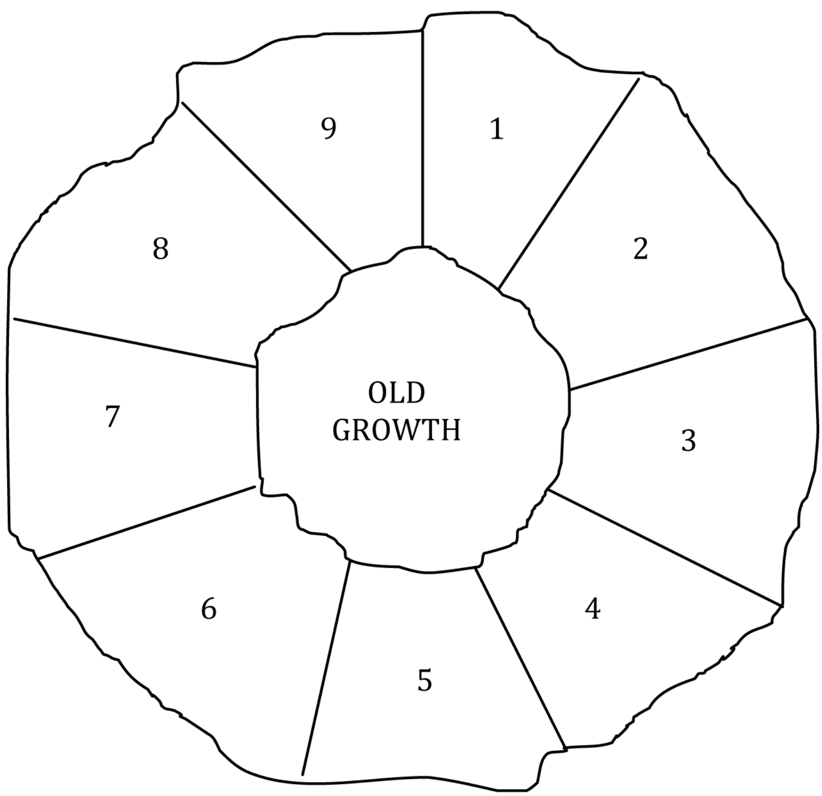

Figure 3. Schematic to demonstrate order of harvest of forest patches in a managed buffer area around an old-growth reserve. The wedges would be logged in sequential order. The entire area would be maintained under forest cover of varying age classes. This approach is based on Harris (1984).

areas was apparently not considered as a whole, so the real costs associated with disturbance and destruction of such a large amount of the Amazon basin were not appropriately weighed against the benefits of fossil fuel extraction. If drilling leases were concentrated in a way that they could be accessed by fewer roads, the overall impact would be much reduced (Carvalho et al. 2001; Soares-Filho 2004; Finer et al. 2008).

When forests are harvested or cleared for agriculture or other purposes, the ability of forest remnants to function as wildlife habitat is usually improved by increasing connectivity among patches (Beier and Noss 1998; Tewksbury et al. 2002; Willson 2004). This can be done by maintaining or creating forest corridors or by ensuring that the matrix of land surrounding the forest remnants can support native wildlife (e.g., Koh 2008). Corridors can also facilitate pollination and seed dispersal (Tewksbury et al. 2002). It should be noted that, although corridors have largely been found to have positive or neutral effects, they do not always benefit intended species (e.g., Hannon and Schmiegelow 2002), and they can have negative effects by funneling movement of predators or disease vectors (e.g., Weldon 2006). When installation or protection of corridors comes at high expense compared with other conservation practices, the costs and benefits must be carefully weighed (Simberloff and Cox 1987; Simberloff et al. 1992). However, when corridors also function as windbreaks or riparian buffers, the benefits are clear.

Vegetation along streams slows water flow, holds soil, and adds material in the form of leaves or woody debris. An overhanging canopy shades the stream and can reduce water temperatures. Forest harvest and conversion to agriculture result in severe changes to riparian vegetation, stream microhabitats, and aquatic life (Heartsill-Scalley and Aide 2003). Riparian buffers are usually designed to protect streams from sedimentation and soil-bound nutrient runoff from adjacent lands. Dissolved nutrients, pesticides, and other pollutants typically require much larger buffer zones (Bentrup 2008). Buffers or wooded stream corridors may also function as habitat or dispersal corridors for terrestrial wildlife (Haas 1995; Machtans et al. 1996) or to improve in-stream habitat quality for fish (Naiman and Decamps 1997; Richards and Hollingsworth 2000). Riparian buffers can be composed of woody or herbaceous vegetation or some combination (Osborne and Kovacic 1993). Buffers installed along headwater streams (in the higher reaches of watersheds) will have effects over a larger downstream area and thus are more valuable to conservation (Tomer et al. 2008). However, the value of land for agricultural production is also likely to vary between the headwaters and lower sections of stream. In the central United States, where most farmers currently use heavy equipment and chemical inputs while facing a restricted growing season, lands that flood seasonally are not desirable for farming, thus farmers lose little income by converting these areas to riparian buffers (Frimpong et al. 2007). In contrast, certain traditional agricultural practices depend on fertile and moist floodplain soils that are regularly replenished (Adams 1986). Removing land from cultivation in these areas would likely have high costs, making installation of riparian buffers more expensive. Biophysical characteristics of land have been shown to be good predictors of the amount of forest cover on private land in a primarily agricultural area and need to be considered in cost-benefit planning and landowner compensation for adopting conservation practices (Frimpong et al. 2006, 2007). The widths required for effective buffers depend on the landform (soil type, slope, geology), adjacent land-use type (forestry, pasture, cultivated field), and objectives (sediment reduction, nutrient reduction, flow regime, in-stream fish and amphibian habitat, wildlife conservation). Although certain recommendations exist for buffer widths, there is still a great need for research to document effectiveness across a range of situations (Coleman and Kupfer 1996; Blinn and Kilgore 2001; Lee et al. 2004).

Agroforestry

Because light is so important to crop growth, most agriculture in forested areas starts by clearing the trees. However, for long-term productivity, maintaining some forest cover may benefit the producer as well as off-farm users of ecosystem services produced on the farm. Agricultural systems that incorporate some tree cover in the landscape include shifting cultivation (or slash-and-burn farming), silvo-pasture, and agroforestry.

Slash-and-burn farming techniques keep most of the farm in native tree cover at different stages of regeneration. After crops are cultivated for a period of three to five years, the land is allowed to rest as a tree fallow, ideally for a period of more than 10 to 20 years during which soil nutrients and productivity are restored. In areas where increasing population pressure has pushed farmers onto steep slopes and otherwise marginal lands or reduced the time of the fallow period, the system breaks down and is no longer sustainable as ecosystem processes degrade and cannot be restored quickly enough to meet the demands of the growing population.

Silvo-pasture systems, defined as agricultural systems where open-canopy and/or low-density trees are grown in livestock pastures, are used because sparsely planted trees can shelter forage crops growing beneath them from intense sun and heat, help to retain moisture in upper levels of the soil, and improve quantities of soil nutrients (Belsky 1993; Dagang and Nair 2003). Further, livestock will eat more and therefore produce more meat or milk when they can feed in the shade rather than in the heat of the sun (Fike et al. 2004). Some tree crops, including legumes, produce fruits or leaves that provide a valuable food source for livestock (Smith 1953; Fike et al. 2004). Farmers may be able to harvest fruit or nut crops, fuel wood, or timber from silvo-pasture systems.

Agroforestry is defined as the intentional co-planting of new or comanagement of existing high-density shade trees with agricultural crops (Bhagwat et al. 2008). It is differentiated from silviculture in that in silviculture, trees are solely managed for the production of fuel, fiber, or timber from the trees themselves. Several globally important cash crops such as coffee, cacao, ginseng, betelnut, and shiitake may benefit from or even require shade conditions that can be provided by growing these species under a native forest canopy or under tree crops (e.g., fruit trees) in the same fields. Maintaining a tree canopy provides multiple ecological benefits, including holding soil, slowing rainfall runoff and erosion, and providing habitat for a greater diversity of native wildlife species. A review of agricultural practices in Mesoamerica found that landscape mosaics with significant tree cover provided important habitat for a large proportion of the native biodiversity (Harvey et al. 2008). Another review reinforced the importance of the distribution of native vegetation on the landscape. As expected, the diversity of native forest birds and insects declines in fields at greater distances from native forest. Importantly, however, the presence of native canopy tree species in agricultural plots can greatly mitigate this effect (Tscharntke et al. 2008). The benefits of agroforestry for biodiversity are threefold (Schroth and do Socorro da Moto 2007): It can maintain habitat by reducing the conversion of natural forest into cultivated land, it can restore habitat quality to land already cultivated, and it can create a more favorable matrix between isolated patches of native forest. Agroforestry can have similar advantages for producers as the intercropping or polycultures of herbaceous species, namely, the diverse architecture of agroforests more efficiently absorbs sunlight, and the variety of root depths and peak demand times creates

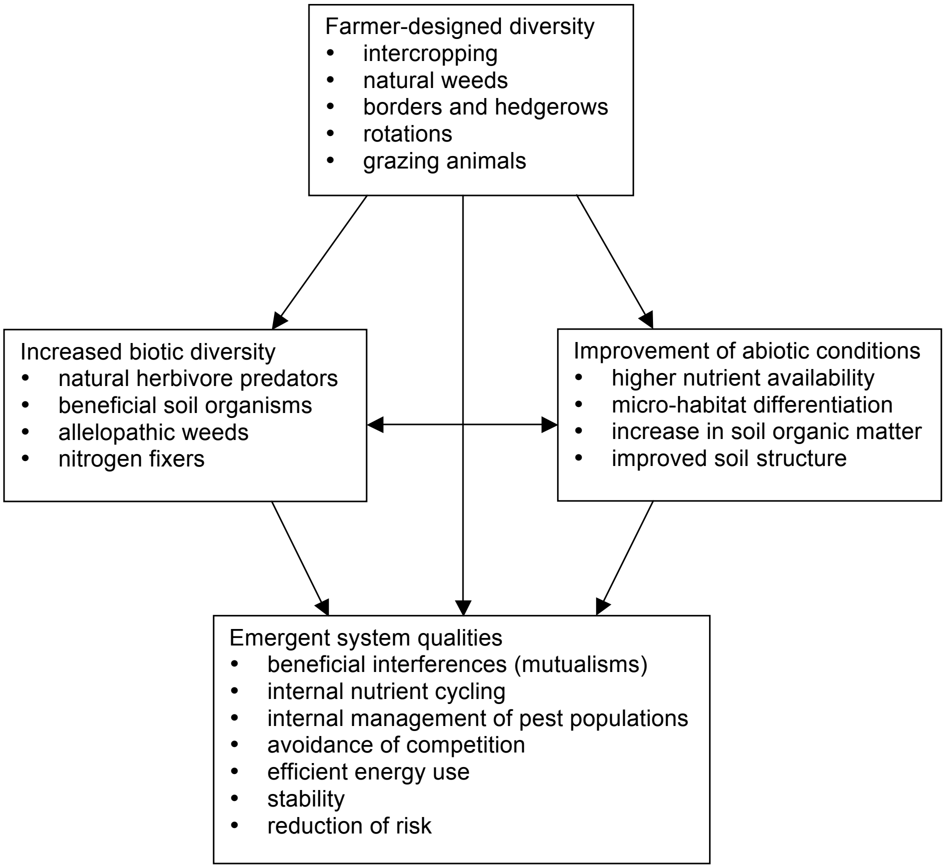

Figure 4. Multiple benefits derived from diversity in agricultural ecosystems (Gliessman 2007).

less competition for nutrients and water. Further, the species mix provides more habitat for beneficial insects and vertebrates, and it can slow the spread of pathogens and pests (figure 4; Gliessman 2007). The emergent system qualities listed in figure 4 can be observed in herbaceous polycultures as well as in agroforestry systems and most especially on farms with diversity (across space and time) within and among fields.

Agroforestry systems that maintain some native trees may provide important corridors or buffers to connect or protect larger areas of native habitat. Even nonnative trees may provide some structural components of wildlife habitat, although the manager must take care not to actively plant known or potential invasive species. Agroforestry that employs native trees may provide significant benefits to local inhabitants that were normally derived solely by living adjacent to natural forest stands.

Field to ecosystem level: Native trees as medicine and wildlife habitat, a community-driven case study of the value of restoring ecosystem services

Around the globe, agroforestry takes many forms ranging from farms that mix cash agricultural crops such as coffee under the canopy of native trees to monocultures of pine or eucalyptus that are ultimately clear-cut and harvested for timber. In one farm-field system in southeastern Madagascar, a local community has worked together with an international team of biologists to develop a medicinal plant-based agroforestry system on its privately owned field/farm system. The story of this medicinal agroforestry project's development is unique and illustrates the value of recognizing and respecting local beliefs and working in the context of those beliefs to protect and restore ecosystem services.

The genesis of the project was in co-author Sarah Karpanty's involvement with a local village for a research study of local raptor communities. For one species, the Madagascar harrier hawk, she found only one nest, located outside of the park boundaries on the edge of a small, subsistence farming village. In fact, 5 of 10 nests discovered during a pilot study were outside of the formal park boundaries.

After discovering the nests, the research team spent time in meetings with the families in ownership of particular field systems where birds were located. In these meetings they asked each family, if possible, if they would exclude the nest trees from any of their subsistence-level slash-and-burn agricultural activities for the three- to four-year period of the study. They all agreed.

The research team returned after a few months and began to check the status of the nests discovered earlier. From a conservation biologist's perspective, the picture that developed was disheartening at best. Within a week, the team found that 5 out of 10 nests, all located outside the park boundary, had been cut down in the process of clearing land for subsistence-level agriculture. At the last nest site visited, there was a bare tree still standing in the center of the blackened field, and in it was the harrier hawk nest, now with three chicks. The farmers had taken the team's request literally; they had not cut the tree and had invested a tremendous amount of effort in creating a fire-break around it. However, the harrier hawk chicks did not survive that season. Without the cooling effect of surrounding forest, they literally baked in the hot subtropical sun.

The village president, Tonga, told the team that he was upset about the incident too and that he wanted to talk about his idea to reforest areas of old farmland with trees of multiple uses to his villagers, especially trees of medicinal value. He recognized that there was very little forest left outside the national park boundaries, and he was worried about the future of his farming community, in particular its ability to harvest medicinal products, for this was prohibited within the national park. He also mentioned that, in his village's belief system, the ancestral spirits reside in the forest, and this was an equally important reason to plant new trees so that the ancestors' spiritual resting grounds would not be destroyed.

It was a meeting of like minds. That day a new partnership was sealed between the villagers and long-term researchers by an offering of the local rum, tokagasy, and a leaf-full of honey to the ancestral spirits. Now, eight years later, Tonga himself has passed away, yet his successor and all the villagers have been working in collaboration with scientists at the nearby field station to plant more than 20,000 native trees on fallow farmland in the village area bordering the national park. Most of the planted trees have medicinal values recognized and utilized by the villagers themselves; those without medicinal value will be used as fruit trees, construction materials, or firewood. An added indirect benefit of the project is that, by planting native trees, the villagers are ultimately creating wildlife habitat for the many threatened and endangered lemurs and other animals that are now confined to the national park. As an incentive for participation in the project, all families in the village were provided hands-on training in reforestation techniques, basic supplies for growing and planting their own native trees such as seedling bags, water buckets, wood to construct a nursery, and help during the planting phase each year. Educational materials for the local schools were also developed in the hope that the multiple values of the project will be communicated across generations.

In some ways, this example is a simple story of a community-based reforestation project that directly benefits the local village by providing trees of medicinal and other values on degraded farmland while providing wildlife habitat. Yet it also illustrates how, at the farm level, individual families and village units can have a profound effect on the watershed and ecosystem by directly restoring ecosystem provisioning services such as food, fuel, and medicine; ecosystem cultural services such as spiritual values; and indirectly, ecosystem regulating services such as erosion and water regulation to what was highly degraded, erosion-prone farmland providing few to no ecosystem services. The other profound lesson is that the motivation for restoring these degraded fields simultaneously came from two sources: foreign biologists with interests in protecting biodiversity and local people with interests primarily in the medicinal, food, and cultural values of the land. If the regional or national governance system had imposed this reforestation project on the villagers with the sole rationale of protecting biodiversity for ecotourism reasons, it likely would have failed within the first few years. However, given the villagers' own strong, multifaceted rationale for the project from its inception, it has been successful to date.

Role of Culture in Ecosystem-Level Management

Pacey's (1983) call to consider a countervailing approach to the dominant economics/technical fix worldview can bring much needed diversity to the planning and design of development projects. For example, in the Madagascar example (textbox above), working with the community to achieve cultural goals was critical for the success of a project that was important for biodiversity conservation as well as local wellbeing. If we decide we are most concerned with "not the material flow from resources through the economy but the immaterial flow to human wellbeing," we must measure success by looking at information beyond economic growth. Such metrics could include levels of education or literacy (among both sexes and across social classes), infant mortality, life expectancy, supplies of food energy (calories) and protein per person per day, availability of latrines or other sanitation measures, and participation in community organizations. These metrics may have much stronger correlations with each other (for instance, infant mortality is strongly inversely correlated with education) than with economic growth. The economics/technical fix encourages us to focus on production. When presented with information on malnutrition, the response is to boost food production. However, as Pacey points out, the real problem with malnutrition is inequalities in consumption, not production. By focusing on CAS, we can examine the variety of factors that are limiting consumption of necessary food items (e.g., production of cash crops on fields that formerly produced subsistence crops, collapse of local farm economies because of subsidized imports), and we can work across various levels to improve the situation.

Pacey's "matrix for assessing different points of view" (table 2; Pacey 1983) illustrates a strategy that can help planners broaden their thinking and incorporate a diversity of approaches. For instance, if the goals and worldviews of both local farmers (e.g., production of crops for subsistence use and markets, maintenance of water supplies) and more distant stakeholders (e.g., water supply, biodiversity conservation, carbon sequestration) are considered together, then programs (e.g., payment for ecosystem services) to achieve multiple goals can be developed (Pagiola et al. 2004).

Development activities have not always recognized the importance of women's role in agriculture and conservation. Especially in many sub-Saharan African countries, women have historically farmed most of the crops consumed in the household. When development projects target men to grow export crops, land that had been used for production of subsistence or locally sold foods often is converted to export crop production. Although this may increase household income, the nutritional status and health of women and children in those households may decline (Bryson 1981; review in Pacey 1983; Shell-Duncan and Obiero 2000). In many cultures, women hold much of the traditional knowledge of sustainable farming techniques and conservation, and use of native plants that may be important for medicinal or cultural practices (Howard 2003). Women's conservation efforts, such as the Green Belt Movement in Kenya, have often been very effective (Deda and Rubian 2004).

Table 2. Matrix (adapted from Pacey 1983) for assessing different points of view on any new development (e.g., installation of water harvest structures, road construction to facilitate transport of crops to market).

Queries	Expert views	User views
Practical benefits and costs		
What benefits are sought?	Very specific benefits (e.g., increased revenue from export crops)	Better living standards in general, including income, health, amenity, housing; reduced risk may be more important than increased production
What costs, what risks, and what environmental impacts are perceived?	Cost of implementation; risks as a statistic to be weighed against benefits	Costs in time, cash, amenity, organization, risk seen in personal and family terms
Who gains which benefits? Who loses?		Lowest income groups may not be able to participate
Status and political advantage		
What is the impact of the project in terms of status and prestige?	Visible progress, good for national prestige; professional advancement for the experts concerned	Status associated with possession of new farm amenity
Who gains or loses status, power or influence?	Some strengthening of central government authority	Some loss of control over lifestyle; fear of bureaucratic power
Basic values		
What is the cultural context?	Scientific/technical; the expert sphere	Domestic/traditional; the user sphere
What are the dominant values?	Technical interest and virtuosity; economic values	Need or users values; family welfare

Notes: The columns representing expert and lay (or user) views are initially blank and are filled in by promoters of the project as a means of testing its appropriateness in the community concerned. The matrix is shown partially completed; in practice, both questions and answers will usually need to be more detailed.

The model system we considered presumed that farmers actually owned the land that they were farming. In such a case, sustainable management practices will benefit the farmer and subsequent generations of his or her family. However, when farmers do not own or have long-term land tenure, their actions will be designed to maximize their short-term gains with no concern for long-term implications. For example, yields are high in the first few years of clearing a new plot for shifting cultivation. Developing an agroforestry plot takes several years with relatively low yield in early years. Without secure land tenure, short-rotation shifting cultivation will be preferred over agroforestry, propagating an unsustainable system over ever increasing areas of land. The ecosystem services of the second land-use scenario discussed above would not be realized. Successful management strategies must then work either to achieve land tenure for farmers or to provide short-term incentives for sustainable behaviors (Rights and Resources Initiative 2008). Farming techniques that provide short-term as well as long-term benefits will be more likely to be adopted in all conditions (Graves et al. 2004).

Another advantage of secure land tenure is the development of knowledge of particular fields, of locally adapted crops, and of knowledge that allows the farmer to work best in the context of surrounding native habitats. Farmers who have worked the same fields over several years (or several generations) can use past experience to implement appropriate management practices and choose crops best suited for particular fields or sections of fields. Traditional knowledge is often undervalued. Cultures that have persisted for long periods in a given system can accurately describe native biodiversity and the food and medicinal value of native plants and animals (Mayr 1932; Berkes 1999; Bumacas et al. 2007; Molnar et al. 2007). Indigenous crops and farming practices are particularly well adapted to the local environment. Although certain traditional practices may not function well as situations change (because of climate change, rapid human population increase, shift to a cash economy), many of the basic techniques are still valuable, and perhaps a new structure for the practices can return them to sustainability (King 1911). The continued use of locally developed crops should be encouraged. Although new varieties may produce higher yields under certain conditions, small farms with high crop diversity have lower risk for dietary imbalances or for complete crop failure (Eilu et al. 2003; Altieri 2004; Negash and Niehof 2004; Thompson et al. 2007). In addition, maintaining the genetic diversity of these traditional crops will be critical for future plant breeding. Detailed knowledge of local crop varieties and wild plant and animal species may be lost as farmers are displaced or their practices are modified. When indigenous languages and cultures are lost, generations worth of knowledge of sustainable farming systems may disappear as well (Cox 2000). Retaining this knowledge and in situ crop diversity (with associated genetics) will be crucial to efforts to feed a growing human population (Berkes 1999; Brush 2004).

Whatever one's worldview, when faced with choices of bettering one's own lot or benefiting society by conserving biodiversity or providing other ecosystem services, we cannot expect individuals to act against their self-interest. The "tragedy of the commons" explains why environmental degradation often results when resources are exploited by many with little or no regulation (Hardin 1968). Either formal or informal regulation of natural resource use is required for such use to be sustainable. In many cases, existing social contracts at the local level (such as those described in the Madagascar textbox above; Ostrom 1990; Berkes 1999; Pei 1999) have functioned well for managing communal lands or other common resources. But even in these cases, the "tyranny of small decisions" can still be important (Odum 1982). What works well for a small community may still have negative implications for downstream residents, for example. As we have come to understand the importance of multiple spatial and temporal scales in ecosystem processes (Lovett et al.

2005) and thus natural resource management (Possingham et al. 2005), it is clear that sustainable management requires the involvement of stakeholders who may not reside in the local community and should include regional and national natural resource managers, planners, and policy makers. Our model example focused on hierarchical levels up to the ecosystem level. It will be necessary to develop a parallel model of the market and policy system and to combine these with the ecosystem model to obtain scenarios that reflect the real complexity in natural resource decision-making. Encouraging a collaborative learning process in which stakeholders use a CAS model to evaluate the effects of alternate strategies and to assign rights and responsibilities may help to create better functioning structures (Wilson 2002). The often contrasting worldviews of stakeholders suggest that a first step should be to describe the "larger set of rights and obligations" required to achieve sustainable management (Berkes 1999). The concept of "bridging social capital" suggests that synergistic goals can be achieved by dynamically managing linkages among stakeholders at different levels of the CAS (Woolcock 1998; Woolcock and Narayan 2000). Where fields are placed with respect to streams and rivers or steep slopes, what percent of the land remains in native vegetative cover, what the condition is of land between native reserves, who has access to certain resources, and who has responsibility to maintain them will all have major effects on the ability to provide ecosystem services, but these decisions cannot be made solely by individuals or even local communities. To achieve the equitable distribution of benefits called for in the International Assessment of Agricultural Science and Technology for Development (IAASTD 2008), it will be necessary to equally distribute the costs as well. Designing, developing, and maintaining the social, political, and economic structures that can sustain coordinated natural resource management decision making at large spatial scales will be the major challenge for the near future.

Conclusions

The ecosystem level of management integrates activities at the field, farm, and watershed levels. Connections to the policy/market sphere are critical, especially when important decisions have effects across political boundaries. Ecosystem services fall into several categories: provisioning, regulating, and cultural services. Simple models such as the scenarios described in this chapter can be used to help evaluate the response of each of these types of services to proposed activities. Real situations, however, involve extreme complexity. Basic principles can help to guide decision-making:

- Long-term sustainability of the ecosystem is critically dependent on the sustainability of the practices adopted by individuals and households who control the smaller land parcels (e.g., fields and farms) nested in the ecosystem. Thus, focus on long-term and large-scale consequences, but include short-term and local incentives to encourage adoption of sustainable practices.
- Maintain local diversity (biological and cultural) and local cycling of materials such as soil amendments to benefit local ecological, economic, and social systems. A focus on local materials and markets can help to balance energy, nutrient, and water flows in a system.
- Work with rather than against the natural environment. Natural systems have natural climatic and disturbance regimes that influence the type of native vegetation and the percent of the land that is in early successional stages at a given point in time. Management systems that incorporate and/or approximate these natural patterns will likely be most sustainable in the long term and meet the different needs across the hierarchy of scales in the complex adaptive system.

Resources

To learn more about efforts to achieve production/economic goals, societal/community goals, and environmental goals simultaneously, readers may wish to investigate the following movements and organizations:

- Ecoagriculture Partners (www.ecoagriculture.org)
- Holistic Management (www.holisticmanagement.org)
- Landcare International (http://www.worldagroforestry.org/sea/landcareinternational/default.asp)

Authorship Statement

C.A. Haas developed the original outline, drafted much of the text, and incorporated comments in revised drafts. S.J. Karpanty wrote the Introduction and the Madagascar textbox. E.A. Frimpong developed the conceptual model example, including figures and tables, and wrote the accompanying text. All authors contributed to the overall concept, organization, and literature review. C.A. Haas is listed as first author because of her lead role. E.A. Frimpong and S.J. Karpanty contributed equally as co-authors. The order of listing here is alphabetical and does not reflect differences in contribution.

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