Land-use choices: balancing human needs and ecosystem function

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Conversion of land to grow crops, raise animals, obtain timber, and build cities is one of the foundations of human civilization. While land use provides these essential ecosystem goods, it alters a range of other ecosystem functions, such as the provisioning of freshwater, regulation of climate and biogeochemical cycles, and maintenance of soil fertility. It also alters habitat for biological diversity. Balancing the inherent trade-offs between satisfying immediate human needs and maintaining other ecosystem functions requires quantitative knowledge about ecosystem responses to land use. These responses vary according to the type of land-use change and the ecological setting, and have local, short-term as well as global, long-term effects. Land-use decisions ultimately weigh the need to satisfy human demands and the unintended ecosystem responses based on societal values, but ecological knowledge can provide a basis for assessing the trade-offs.

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People transform landscapes to obtain food, fiber, timber, and other ecosystem goods. This basic aspect of human existence holds true whether a subsistence farmer is growing food to feed his family from marginal lands in southern Africa or a multinational conglomerate is fertilizing and irrigating land in the midwestern US to export crops worldwide. The intended consequence of this land use is clear – to appropriate primary production for human consumption (Vitousek *et al*. 1986). The unintended consequences for the watershed, atmosphere, human health, and biological diversity often remain hidden. The implicit assumption is that the intended consequence of appropriating primary production for human consumption outweighs the unintended consequences for other ecosystem functions.

In a nutshell:

- Land-use change to provide food, fiber, timber, and space for settlements is one of the foundations of human civilization
- There are often unintended consequences, including feedbacks to climate, altered flows of freshwater, changes in disease vectors, and reductions in biodiversity
- Land-use decisions ultimately weigh the inherent trade-offs between satisfying immediate human needs and unintended ecosystem consequences, based on societal values
- Ecological knowledge to assess these ecosystem consequences is a prerequisite to assessing the full range of trade-offs involved in land-use decisions

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Land-use change is intricately related to both economic development and the ecological characteristics of the landscape. Within a particular region, land use potentially follows a series of transitions that parallel economic development – from wildlands with low human population densities, to frontier clearing and subsistence agriculture with the majority of the population employed in food production for local consumption, to intensive agriculture supporting mainly urban populations (Figure 1; Mustard *et al*. in press). Regions might pass through these transitions rapidly over a period of years, or slowly over a period of centuries. In some cases, a particular region may never complete the full transition if economic conditions do not enable the infrastructure for fertilizer, irrigation, or transport; if consumer demand for products from intensive agriculture is too weak; or if arable and accessible land is not available.

We can see examples of different land-use transitions occurring throughout the world. Parts of the Amazon basin, for example, are currently experiencing a rapid transition from wildlands to intensive agriculture within a period of years, as forests that were initially cleared for pasture are now being converted to intensive agriculture in areas where infrastructure and ecological conditions are conducive to this type of usage (Laurance *et al*. 2001). Other regions, such as the Indian subcontinent and China, experienced frontier clearing many thousands of years ago, and much of the agricultural activity is still for local subsistence (Ellis and Wang 1997), except in pockets such as the Punjab where fertile soils and infrastructure inputs resulting from the Green Revolution have completed the transition. Other parts of the world remain in the subsistence stage, with few near-term prospects for moving through the transition to intensive agriculture. In sub-Saharan Africa, for instance, the vast majority of the population obtains food from subsistence farming or pastoralism.

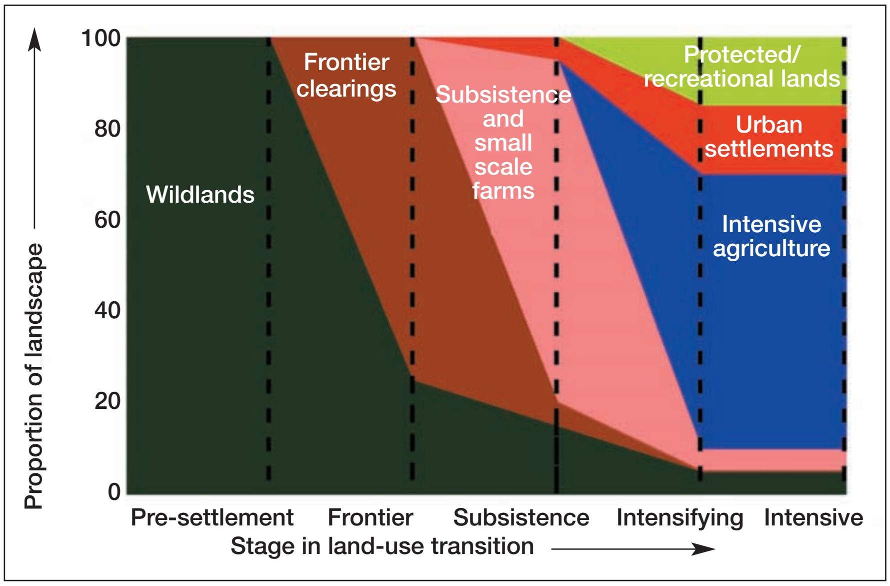

Figure 1. *Schematic representation of transitions in land use in a country or a region within a country. Different parts of the world are in different stages of this transition, depending on economic and ecological conditions. Adapted from Mustard* et al. *(in press).*

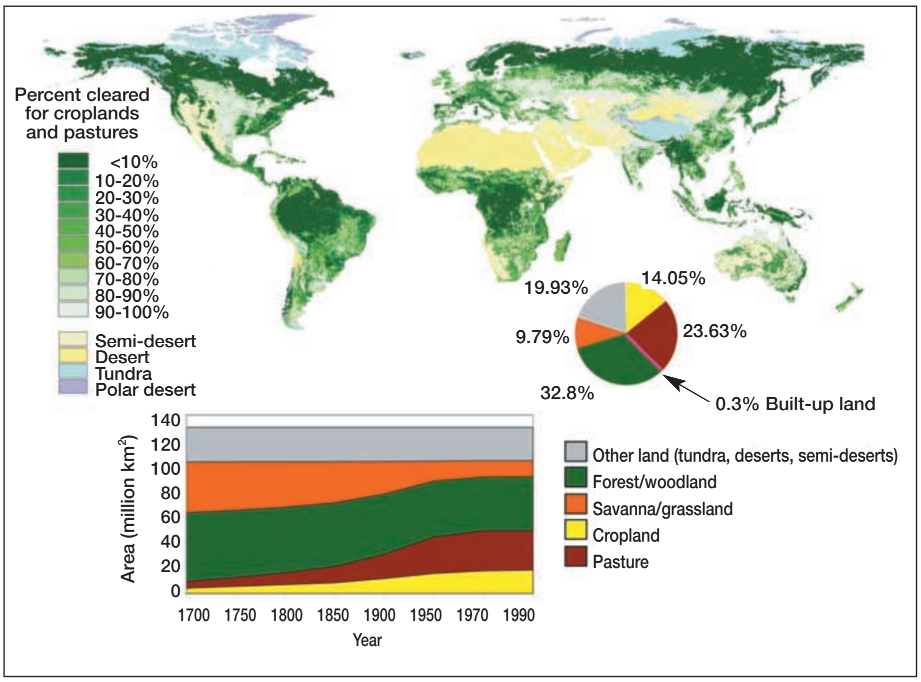

Figure 2. *The map (top) illustrates the extent of human land use (including conversion to croplands, pastures, and urban areas) on the planet in the early 1990s. The only large areas that are still not overwhelmingly exploited for agriculture or human settlements include the tropical rainforests (mostly in the Amazon and Congo basins, and the Indonesian archipelago) and the boreal forests (largely in Canada and Russia). The plot (bottom) shows that there has been a large increase in the amount of land devoted to agriculture (croplands and pastures) over the past 300 years. Adapted from Foley* et al. *(2003) and Foley* et al. *(unpublished).*

At the other end of the transition scale, much of the cropland in the eastern US is returning to forest (Williams 1989; Foster 1992) while intensive agriculture in the Midwest provides food for consumption in distant locations. Puerto Rico has witnessed a transition from having 10% of its land covered with forest in the 1940s to more than 40% today, with a shift from agriculture to manufacturing and migration from rural to urban areas (Grau *et al*. 2003). Similarly, forest cover has increased in parts of the Ecuadorian Amazon, with a shift from cattle ranching to crops for urban and export markets (Rudel *et al*. 2002). Yet other regions experience cycles as they pass through these stages in land-use transition; for example, the Central American Mayan forests which are wildlands today once supported dense human populations during the peak of that civilization (Turner II *et al*. 2003), and the Amazon Basin, where large-scale transformation of landscapes existed around 1200 to 1600 AD in places now considered to be "pristine" (Heckenberger *et al*. 2003).

The land area within each stage of the land-use transition varies from continent to continent and changes over time with economic development, population growth, technological capabilities, and many other factors. Few wildlands remain unaffected by human presence, roads, or other infrastructure. Sanderson *et al*. (2002) estimate that 83% of the land surface is either directly or indirectly affected by human influences. The remaining large tracts of wildlands are located where it is too cold (boreal forests of Canada and Russia, and the Arctic tundra), too hot (desert regions of Africa and Central Australia), or too inaccessible (the Amazon Basin).

Today, approximately 33% of the land surface is under agricultural use, either as cropland (12%) or pasture (21%) (Figure 2). In arid and semi-arid regions, managed grazing – the single largest form of land use – takes place in areas often considered to be "wild open spaces" or wildlands (Goldewijk and Battjes 1997; Asner *et al*. in press a). The transition from wildlands to agricultural use over the past several hundred years has reduced previously forested lands by 20 to 50% (Matthews *et al*. 2000), and over 25% of grasslands have been converted to cropland (White *et al*. 2000). Urban areas cover only a small percentage of the landscape, but the resident populations generate a food demand that alters land use over a much larger area.

Subsistence agriculture, including both cultivation of crops and grazing domestic animals on rangelands, supports about half the world's population (Marsh and Grossa Jr 1996). In the coming decades, the expansion of cropland areas is likely to be a major factor in sub-Saharan Africa and Latin America, but elsewhere the mainstay of food production will come from intensification of agriculture through higher yields and more multiple cropping (Alexandratos 1999; Turner II 2002).

Ecosystem consequences of land-use change

The implications of these land-use transitions for ecosystem function are profound. In addition to providing food, fiber, fuelwood, and space for human settlement, ecosystems also perform a vast array of other functions necessary for life (Daily 1997; Millennium Ecosystem Assessment 2003). For example, ecosystems provide habitat for other plant and animal species, regulate climate by modulating energy and water flows to the atmosphere and sequester carbon that would otherwise reside in the atmosphere as a greenhouse gas, maintain the flow of freshwater into streams, and regulate vectors that transmit disease (Table 1). Land-use change enhances the share of primary production for human consumption, but decreases the share available for other ecosystem functions.

These land-use transitions offer a general framework for identifying different ecosystem consequences characteristic of different stages. As forests are cleared in the frontier stage, for example, carbon dioxide is emitted to the atmosphere as a result of clearing, burning, and vegetation decay. During the intensive stage in the transition, however, the major consequence for greenhouse gas emissions is likely to be nitrous oxide emissions from fertilizer use; carbon dioxide emissions will be much less important, since the initial biomass has already been removed (Galloway *et al.* in press). Other ecosystem responses such as disease regulation and biodiversity also follow characteristic responses, depending on stage in the transition (Figure 3). Habitat fragmentation alters biodiversity in the initial clearing stage, but in the subsistence stage there are substantial declines in mammal populations associated with bushmeat hunting (Newmark *et al.* 1994).

Ecosystem responses to land-use change also vary in different ecological settings, even for the same type of land-use transition. For example, conversion to agricultural land in temperate and boreal latitudes may lead to a cooling of the surface as a result of increased albedo (amount of incoming light reflected back to the atmosphere) associated with a brighter land surface (Bonan 1999). The same type of conversion in tropical latitudes has precisely the opposite warming effect, where surface temperature increases with reduced transpiration in crops and pastures compared with high-biomass tropical forests (Costa and Foley 2000; Bounoua *et al.* 2002; DeFries *et al.* 2002b). The consequences of urbanization also vary with ecological setting. Urbanization in forested systems probably increases the tendency to flash floods, as water runs off impervious surfaces rather than percolating through the soil. However, in arid systems, urbanization might reduce this tendency due to the greater number of lawns and other green spaces.

Grazing has opposing impacts on vegetation under different ecological conditions. Heavy grazing is now widely implicated in the expansion of woodland vegetation in formerly open grassland and savannas in temperate lati-

Table 1. Some ecosystem functions altered by land-use change

Ecosystem function	Role of landscape in providing function	Example of altered function with land-use change
Ecosystem goods (food, fiber, fuelwood)	Provides primary production for human appropriation	Conversion to cropland increases fraction appropriated for human consumption
Provision of freshwater	Regulates flow of water to streams	Urbanization increases tendency to flash floods from storm runoff
	Maintains water quality	Agricultural runoff increases nutrient loads in streams
Climate regulation	Sequesters greenhouse gases through biogeochemical cycling	Tropical deforestation releases carbon dioxide to the atmosphere
	Exchanges water, energy, and momentum with atmosphere	Forest removal increases albedo and cools surface
Disease regulation	Restricts habitat for disease vectors	Deforestation increases human–primate contacts and spreads zoonotic diseases
	Maintains healthy climate	Urbanization creates heat islands
Biological diversity (genetic resources, biochemicals, cultural benefits)	Provides habitat for plant and animal species	Forest conversion increases habitat fragmentation
Soil fertility	Replenishes soil nutrients	Increased soil erosion from clearing depletes fertility

Ecosystem response	Stage in transition: Frontier	Subsistence	Intensive
Greenhouse gas emissions regulating climate	Carbon dioxide emissions from clearing vegetation	Methane emissions from ruminants	Nitrous oxide emissions from fertilizer use
Disease regulation	Zoonotic disease from human exposure to other primates	Diseases transmitted from domestic animals	Exposure to heat waves from urban heat islands
Biological diversity	Habitat fragmentation and loss	Hunting for bushmeat	Monoculture

Figure 3. *Examples of varying ecological responses to land-use change according to stage in the land-use transition.*

tudes (Archer *et al*. 1995; Asner *et al*. 2003); in the humid tropics, ranching systems decrease woodland and forest cover, by up to 15 000 km^2 per year in the Brazilian Amazon alone (Houghton *et al*. 2000). The ecological community's ability to quantify these varying responses to land-use change in different stages of the transition and in different ecological settings is only just beginning to emerge.

Previous efforts have identified ecological principles for guiding land-management decisions (Dale and Haeuber 2001). Such principles highlight the importance of varying time scales of ecological processes, local environmental factors such as topography, climate, and soils that constrain land-use decisions in a particular place, species that control ecological processes disproportionate to their abundance, disturbances such as fire and flood that affect ecosystems, and the spatial configuration of habitat fragments that influence ecosystem response. Applying these ecological principles to quantify the way in which different types of land use in different ecological settings alter ecosystem function is a prerequisite for assessing the trade-offs from land uses designed to satisfy immediate human needs.

Time and space scales of ecosystem responses

Ecosystem responses to land use vary in space and time, and assessing trade-offs associated with land-use decisions requires explicit recognition of the scale of analysis. The increased tendency of a stream to flash flood in response to urbanization, for example, occurs on short time scales of minutes to hours over relatively small areas. Climate responses to greenhouse gas emissions, on the other hand, occur over decades to centuries on continental to global scales, and species extinction as a result of landscape fragmentation occurs over decades as population sizes dwindle.

Spatial scales also vary; for example, land-use change in uplands could have distant consequences in the form of flooding downstream (Costa *et al*. 2003). Deforestation in the tropical lowlands of Costa Rica alters convection of moisture to the atmosphere and leads to drier conditions for upland forests (Lawton *et al*. 2001). If the spatial scale of analysis does not encompass the larger area with sufficient spatial detail, ecosystem responses will be overlooked or predictions will be inaccurate.

Assessments of trade-offs associated with land-use change are only meaningful if the spatial and temporal scales of analysis are carefully defined and explicitly stated. Too narrow a definition of either can result in a misperception of the problem. If soil nutrients decline over time under agricultural use, or if deforestation affects climate or streamflow in distant locations, the perceived impact is crucially dependent on the time period chosen for analysis.

Long-term and far-away responses to land-use change are not always obvious. If land use reduced habitat and the abundance of a top predator declined, for example, the effect could cascade into population expansions for prey species at lower trophic levels (Carpenter and Kitchell 1993; Terborgh *et al*. 2001). A change in disturbance regime, such as the intensity or frequency of flood or fires, could alter habitats for maintaining biodiversity, change the fluxes of carbon and other greenhouse gases to the atmosphere, and affect a variety of other ecosystem functions. These effects might not be apparent for many years.

Non-linearities and thresholds in ecosystem responses

Ecosystems are complex, dynamic systems with interactions between nutrients, plants, animals, soils, climate, and many other components. A linear response to land-use change – for example, a decline in water quality from agricultural runoff in direct proportion to the area undergoing conversion to agriculture – is unlikely in such complex systems. The more common ecosystem response is non-linear, so that small changes in land use would have large ecosystem consequences, or vice versa, depending on the degree of land-use change.

One example of a non-linear response is the application of nitrogen fertilizer for intensive agriculture and nitrate leaching into the Mississippi River system, ultimately contributing to the "dead zone" in the Gulf of Mexico (Donner *et al*. 2002). The application of nitrogen fertilizer involves a trade-off between increasing crop yields and nitrate leaching. Balancing an objective of maximum crop yields with minimum damage to coastal fisheries requires knowledge of the response of nitrate leaching to fertilizer application (Figure 4). In this example, fertilizer application beyond point "A" results in negligible increase in crop yield, but substantial nitrate leaching. A decision to apply fertilizer greater than point "A" trades small

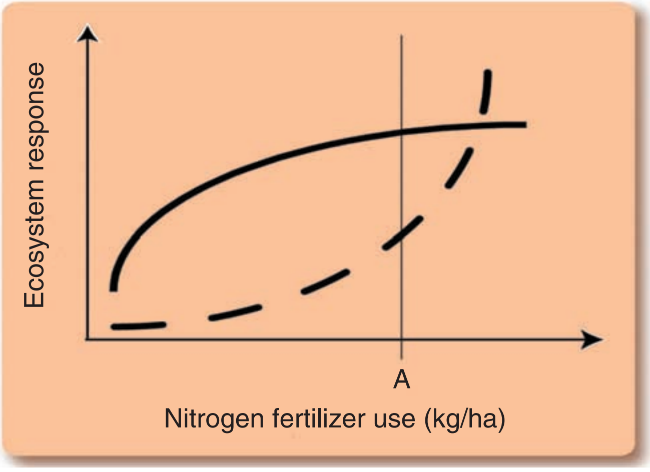

Figure 4. *Non-linear responses of crop yields (solid line) and nitrate leaching (dashed line) to fertilizer application.*

increases in crop yield for large increases in nitrate leaching. A decision to apply fertilizer less than point "A" trades small decreases in nitrate leaching for foregone large increases in crop yield. To the extent that the shape of the response curves can be quantified, land-use decisions can account for these types of non-linear responses to determine the most desirable alternative.

Even more complex is the non-linear interaction between processes occurring simultaneously but at different temporal and spatial scales. Many managed grazing systems faltered in the southwestern US during the 1950s, as a major regional-scale drought took hold and persisted for nearly a decade (Fredrickson *et al*. 1998). Areas which were once productive for cattle ranching continued to be grazed well into the drought period, denuding very large areas of grassland. Cattle were eventually removed, as ranching ceased in some regions and waned in many others, but when precipitation returned to the region, there was a relatively sudden (non-linear) increase in woody vegetation across many large tracts of land (Buffington and Herbel 1965). The proliferation of woody vegetation was a consequence of heavy grazing that had removed herbaceous species, but these southwestern arid and semi-arid regions were pushed across a bioclimatic threshold induced by the interaction of land management and climate variability.

Ecosystems may also respond to land use via thresholds, often perceived as "the straw that breaks the camel's back". Such is the case when population abundances dwindle to the point where persistence of the species is no longer viable, resulting in a population crash. Many examples of this process come from Hawaii, where endemic honeycreeper bird populations have gone extinct following large-scale habitat loss from human settlement and agricultural expansion. For many species, fragmented habitat persists only at higher (cooler and wetter) elevations (Benning *et al*. 2002). The smaller parcels of remaining habitat no longer carry the rarest species, and avian malaria is moving to higher elevations as a result of climatic warming, pushing bird populations below the number of individuals needed to maintain a viable population.

Understanding the non-linearities and thresholds in ecosystem responses to land-use change is challenging. For those responses where ecological knowledge is available, communicating the response of ecosystem function to land-use change is straightforward for one or a few ecosystem functions. With a larger number of ecosystem functions responding at multiple scales, portraying the responses to land-use change becomes unwieldy (Heal *et al*. 2001). Quantifying and portraying this complexity to be useful for land-use decisions is a major challenge to the ecological community.

Assessing trade-offs from land-use decisions

Land-use decisions must ultimately balance competing societal objectives based on available information about the intended and unintended ecosystem consequences. Objectives might include increasing crop production or revenue from timber on the one hand and maintenance of biodiversity, watershed protection, or any number of other ecosystem services on the other hand. Ecological knowledge to quantify the ecosystem responses in physical units underpins our ability to assess the trade-offs. Decision makers can only take the full range of consequences into account if the consequences are identified and quantified to the extent possible (Figure 5).

Decision makers have been hindered from taking account of the full range of ecosystem consequences, partially because it is not possible with current scientific

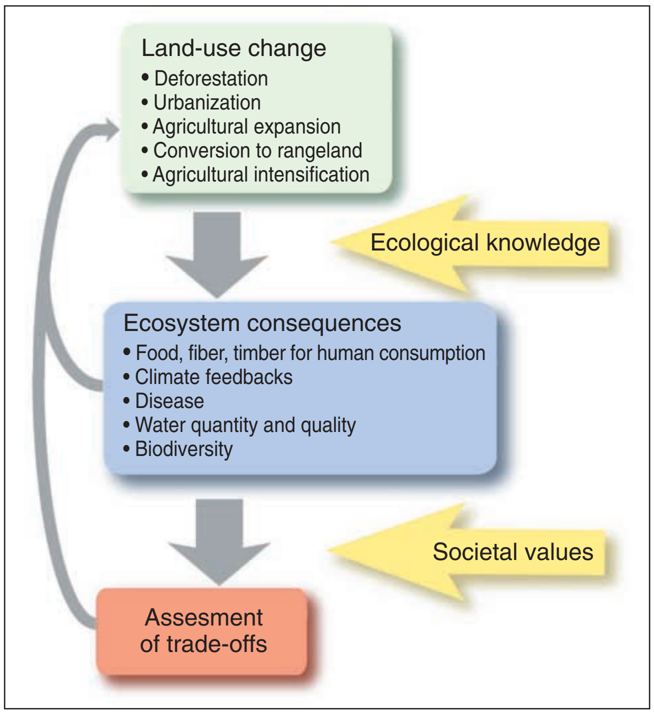

Figure 5. *Relationship between land-use change, ecological knowledge to assess ecosystem consequences, and societal values to assess trade-offs associated with land-use decisions.*

understanding to identify and quantify them over the appropriate temporal and spatial scales and to evaluate them in commensurate units. A number of case studies have quantified individual ecosystem consequences of land use, for example nitrogen pollution to the atmosphere and aquatic systems associated with intensive fertilizer use in the Yaquii Valley, Mexico (Matson *et al*. 1997; Turner II *et al*. 2003), loss of biodiversity from forest fragmentation (Pimm and Raven 2000), and carbon dioxide fluxes to the atmosphere from tropical deforestation (Achard *et al*. 2002; DeFries *et al*. 2002a). Fewer studies quantify the full suite of responses, and fewer still assess the consequences against the positive benefits for society.

We propose that the use of ecological knowledge as input to land-use decisions rests on the following premises.

Premise 1: Land use inherently involves trade-offs

The positive benefit from appropriating ecosystem goods for human consumption is a valid objective even if other ecosystem consequences might be adversely affected. Using ecological knowledge as input to decision making implies highlighting not only the negative ecosystem consequences, but also the benefits in terms of increased yields, revenue from timber, or some other measure of societal advantages. At the same time, it is misleading to make land-use decisions based solely on the immediate societal benefits without weighing the consequences for ecosystem function and, ultimately, the impacts of changes in ecosystem function on society.

Premise 2: Quantifying the full suite of ecosystem responses to land-use change is a prerequisite to assessing these trade-offs

Land-use decisions involve weightings placed on different ecosystem consequences according to their societal value or translation into monetary or other commensurate units, using techniques available from environmental economics (Pagiola *et al*. in press). Often, this process does not explicitly involve the full suite of ecosystem responses and only considers the positive benefits from land-use change. Ideally, the full suite of ecosystem responses at varying spatial and temporal scales should be considered explicitly. The ability to quantify the ecological response in physical units is a prerequisite, and facilitates the further step to assess trade-offs based on societal values (Figure 5). A land-use decision – for example, converting forests to agricultural land – can account for ecosystem consequences such as biodiversity, watershed health, and climate feedbacks to the extent that these consequences can be estimated based on ecological knowledge.

A simple yet powerful approach to portraying these trade-offs is to use a "spider diagram" to depict changes in ecosystem function associated with different land-use alternatives (Figure 6). While simple in concept, such a diagram raises a host of questions. Which ecosystem functions should be included? What are the appropriate units to measure them? Can they be quantified based on current scientific understanding? Should long-term consequences such as species extinction debts (Pimm and Raven 2000) and far-away consequences such as climate change from greenhouse gas emissions be included, or only the near-term and local consequences?

Understanding the full suite of ecosystem consequences requires quantifiable and measurable indicators for each of the ecosystem functions (NRC 2000; Millennium Ecosystem Assessment 2003; Table 2). Quantities depicted could be an absolute measure (eg tons of carbon stored), a measure relative to a previous quantity (percentage change in storage), or an amount relative to a "potential" or ideal "sustainable" amount (percentage difference from maximum). To the extent that these quantities can be estimated, a diagram such as Figure 6 illustrates the ecosystem responses. In reality, the ability to quantify the ecosystem responses and reduce them to commensurate units is not straightforward and is fraught with uncertainty. A conceptual structure for explicitly estimating responses and assessing trade-offs, however, can highlight the possible responses and reveal otherwise hidden assumptions.

To the extent that ecological knowledge can quantify the ecosystem responses at varying scales, a series of spider diagrams representing different scales can inform decision

Table 2. Examples of measurable indicators appropriate for assessing short-term, local scale and long-term, global scale trade-offs associated with land-use change

Ecosystem function	Indicators appropriate for assessing short-term, local-scale trade-offs	Indicators appropriate for assessing long-term, global-scale trade-offs
Crop production	Calories/person for local consumption	Revenue from food export
Climate regulation	Rainfall from local convection	Greenhouse gas emissions altering global climate
Disease regulation	Incidence of disease locally	Spatial range of disease vectors
Biodiversity	Local species richness	Extinctions of endemic species
Soil fertility	Soil erosion in catchment area	Requirements for fertilizer to replenish fertility lost from long-term leaching
Freshwater	Groundwater recharged locally	Incidence of downstream flooding

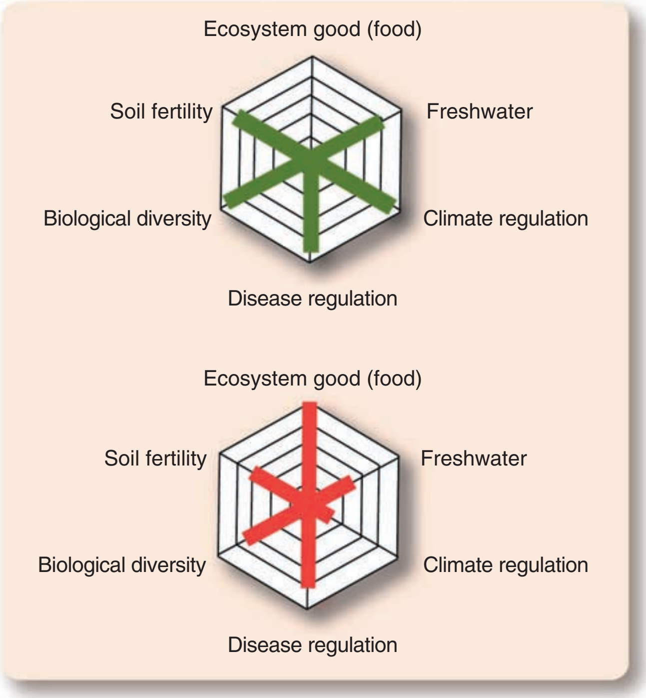

Figure 6. *Illustration of hypothetical trade-offs in ecosystem responses before (top) and after (bottom) land-use change, including intentional appropriation of ecosystem good (eg food) and unintentional ecosystem effects.*

makers about the trade-offs. Appropriate units of analysis probably vary at different scales (Table 2). Crop production, for example, might be more usefully quantified in terms of calories for local consumption if land-use change is for the purpose of feeding local populations. Revenue from agricultural exports is a more applicable unit for analysis for national-level concerns. Likewise, the local response of climate regulation might be measured by changes in rainfall from altered local convection, while a longer time scale of analysis would include greenhouse gas emissions that alter global climate patterns. Explicit recognition of the different ecosystem responses at these varying spatial and temporal scales is fundamental to understanding the tradeoffs involved in land-use decisions.

■ Identifying the "win–win" and "small loss–big gain" opportunities

Graphical depictions such the one shown in Figure 6 are simple and readily communicable to decision makers, but it is difficult to portray non-linearities and thresholds in ecosystem responses to land-use change. Ideally, ecological analysis can identify the "win–win" approaches whereby societal benefit from land–use change increases as ecosystem function is preserved. An example of this is seen in the well known case of the cost-effective preservation of the watershed to maintain the quality of New York City's drinking water. In that case, preserving the watershed by limiting suburban development (a "win" for ecosystem function) was less costly than building a water-treatment plant to meet water quality standards for New York City's water supply (a "win" for immediate societal needs) (Daily and Ellison 2002; Figure 7).

A more common situation is likely to contain non-linear ecosystem responses, so that the challenge is to identify opportunities for "small loss–big gain" (a small compromise in immediate societal benefit for a big gain in ecosystem function, or conversely a big gain in social benefit with only a small loss in ecosystem function). For example, lowland riparian areas cover approximately 3% of the Greater Yellowstone ecosystem and are important breeding areas for maintaining populations of some bird species. Exurban development of rural homes around Yellowstone National Park is occurring in these same habitats (Hansen *et al*. 2002). Restricting development in this small percentage of the landscape (a small compromise in immediate societal benefit) will provide a disproportionate advantage to bird populations (big gain in ecosystem function).

Another example of "small loss–big gain" comes from the tropical timber industry. Conventional logging practices have traditionally been operations that leave the forest severely damaged and ecologically impoverished. The advent of reduced-impact logging (RIL) methods has led to demonstrably lower canopy damage levels, faster forest recovery rates, and reduced fire susceptibility (Pereira *et al*. 2002). However, RIL costs more, due to increased demand for technical expertise, and it leaves some high

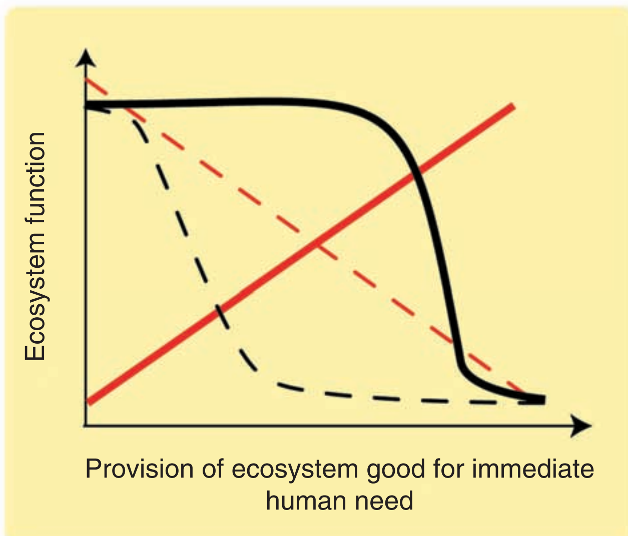

Figure 7. *Examples of possible relationships between land-use change to provide ecosystem goods for human needs and ecosystem function, including "win–win" (red) in which immediate goal (water purification) increases with longer-term goal to maintain ecosystem function (land preserved), and "small loss–big gain" (black) in which small reduction in satisfying immediate goal (number of rural homes) has major benefit for long-term ecosystem goal (breeding habitat). Other possibilities include "win–lose" (dotted red line) and "big loss–small gain" (dotted black line).*

value species standing. The net outcome is less forest fragmentation over time (Asner *et al*. in press b) and possibly shorter harvest cycles (J Zweede pers comm). Small "losses" in cost and in leaving certain species results in "gains" as a result of the more sustainable timber practices, better forest condition following extraction, and thus a cascade of positive ecological repercussions.

Ecological analyses to identify such opportunities for "small loss–big gain" based on understanding of non-linear responses of ecosystem function to land-use change can provide practical alternatives. Other, less desirable but possible relationships between land-use change to satisfy immediate human needs and ecosystem function can be categorized as "win–lose" and "big loss–small gain".

Conclusions

We propose a few simple principles that provide the building blocks for assessing the range of ecosystem responses to land use. Such principles underpin the ability of the ecological community to provide useful scientific information as input to land-use decisions.

(1) Ecosystem responses to land use characteristically vary according to stage in the transition from frontier clearing to intensive human-dominated landscapes and according to the ecological setting. These characteristic responses provide the basis for understanding possible consequences of future land-use decisions.
(2) Land-use decisions often result in trade-offs between intentional appropriation of ecosystem goods to satisfy human needs and unintended ecosystem responses. Balancing the trade-offs ultimately depends on societal values.
(3) A prerequisite to assessing trade-offs inherent in land-use decisions is quantitative analysis of the full range of ecosystem responses, including both the intended ecosystem goods and unintended ecosystem consequences. Analyses need to explicitly consider the consequences at a range of temporal and spatial scales.
(4) Ecosystems are likely to respond in a non-linear manner to land use. These non-linear responses offer the opportunity to identify land-use alternatives with small losses in satisfying immediate human needs but large gains in maintaining ecosystem function.

With increasing population and development pressures, there is little doubt that land-use change will continue over the coming decades, as food demand increases and urban areas expand in many parts of the world. These land-use changes will appropriate an increasing share of primary production to satisfy human needs while simultaneously altering many other functions of the landscape, ranging from regulation of disease vectors to species habitat to freshwater flows. Quantifying the trade-offs between meeting immediate societal needs for resources such as food, fiber, timber, and space and other less-intended consequences for ecosystem function is a major challenge for the ecological community.

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