Trade-Offs in Land-Use Decisions: Towards a Framework for Assessing Multiple Ecosystem Responses to Land-Use Change

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People alter the landscape primarily to appropriate ecosystem goods such as food, fiber, and timber for human consumption. Unintended consequences for ecosystems vary according to the type of land-use change, e.g., forest clearing for agriculture, grassland conversion for grazing, or urban expansion, as well as the underlying ecological characteristics, e.g., humid vs. dry, phosphorus vs. nitrogen-limited, or tropical vs. temperate. The ecosystem responses potentially alter future abilities to provide ecosystem goods and influence future land-use decisions. This volume addresses five major ecosystem responses to land-use change: hydrological, climatic, biogeochemical, human health, and biological diversity. The chapters summarize current knowledge from the perspectives of different disciplines and present analyses from many parts of the world in different ecological and socioeconomic settings. This introductory chapter develops a framework for understanding and communicating the multiple ecosystem responses as an essential input to societal decisions about land use.

1. INTRODUCTION

People have been altering the land surface since the beginning of human civilization [*Turner II and McCandless,* in press]. More than 10,000 years ago, people replaced existing vegetation with plant species more suitable for human consumption. Where water, soil, or topography was more limiting, people grazed their livestock on the existing vegetation. Where access to waterways and other modes of transport permitted, people built settlements that grew into cities. People have also long relied on forests for fuelwood, timber, and a host of other useful products.

This extraordinary scope of human ingenuity is reflected on today's landscape. The major breadbaskets of the world in North America, Argentina, Australia, and Western Europe are vast expanses of highly mechanized farming. Although the world's agricultural production is currently ample to sustain the planet's

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population of more than 6 billion people [*Alexandratos,* 1999], uneven distribution and purchasing power mean that approximately 50% of the population relies on small scale or subsistence farming, often in less suitable conditions for climate, soil, topography, and access to markets [*Dixon et al.,* 2001]. Villages and small agricultural plots permeate these rural landscapes throughout Asia, sub-Saharan Africa, and Latin America. Some of the world's most materially poor people eke livelihoods from grazing livestock in drylands, resulting in visible reductions in plant cover. The mark of timber extraction can also be seen throughout the world's forests. Urban areas house about half of the world's population but cover less than 3% of the world's land surface, though the demand for water, food, and other commodities affects landscapes far beyond.

These imprints on the landscape have vastly altered the world's ecosystems. Klein Goldewijk [this volume] chronicles the large transformations of ecosystems throughout history and the acceleration in the last few centuries. Although ecosystem transformations have underpinned the planet's ability to support the human population at increasing standards of living, concerns about the effects on soil fertility and degradation date as far back as Plato. Examples throughout history illustrate that local repercussions of these ecosystem transformations have undermined or at least contributed to the decline of past societies, such as in Mesopotamia, the Indus Valley, and the Southwestern US [*Redman,* 1999]. Other examples show the importance not just of ecosystem transformation but land management in either exacerbating or alleviating the negative ecosystem consequences of land-use change. Potter et al. [this volume] discuss the major role of soil conservation and tillage practices in the Midwestern U.S. in controlling soil erosion and sedimentation in the mid 1930s. Foley et al. [this volume] illustrate the negative consequences of land management and fertilizer application for nutrient fluxes to Mississippi Basin-river systems since the advent of synthetic fertilizers after World War II.

In this chapter, we examine a framework to assess ecosystem responses to land-use changes and evaluate the conditions under which these responses may alter the ecosystem's ability to support land use in the future. The chapters that follow in this volume synthesize current understanding of ecosystem responses to land-use change and highlight the challenges for implementing this framework in land-use decisions. We consider responses at spatial scales ranging from local to global and temporal scales from immediate to future generations. Our premise for this volume is that land-use decisions often involve trade-offs between intentional appropriation of ecosystem goods for human consumption such as food, fiber, and timber and unintended ecosystem responses such as flooding, habitat loss, and nutrient runoff [*DeFries et al.,* 2004]. These unintended responses potentially affect the functioning of ecosystems and hence their ability to continue to provide ecosystem goods. Balancing the trade-offs ultimately depends on societal values. The scientist's role, in our view, is to develop the understanding necessary to quantify the ecosystem responses to different types of land-use change in different ecological situations. This understanding is one component against which society can weigh the economic and other societal benefits of land-use change.

This volume intentionally does not address the full complexity of the emerging disciplines of land change science and sustainability science [*Lambin et al.,* 2002; *Turner II,* 2002; *Turner II et al.,* 2003]. A comprehensive understanding involves: the driving forces behind land-use change, including economics and markets, human behavior, international and national policies, institutions, biophysical conditions and availability of

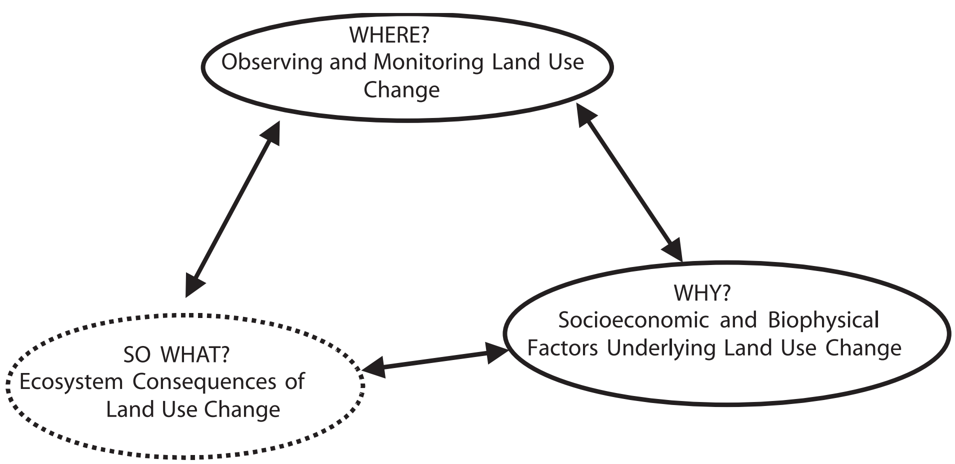


Figure 1. Components of the emerging discipline of land-change science. This volume mainly addresses the current state of knowledge of the "so what" component.

technology to project future change (i.e., why does land-use change occur?); observations and monitoring to identify patterns and locations of land-use change (i.e., where is land-use change occurring?); and analysis of the ecosystem consequences of land-use change and the feedbacks to future land-use options (i.e., so what?) (Figure 1). We focus mainly on the latter in this volume, intending to contribute to the emerging discipline through a focused synthesis of this smaller subset. The volume includes contributions from disciplines once only tangentially involved in land change science, such as hydrology, atmospheric sciences, and public health, to explore the multiple ecosystem consequences and inherent trade-offs from different types of land-use change in different parts of the world.

The following questions have motivated this volume:

1. *What are the major consequences of land-use changes for ecosystems and their ability to provide goods and services in the future?*
2. *How do ecosystem responses vary with type of land use, stage in the land-use transition, and biophysical setting?*
3. *What are the appropriate temporal and spatial scales for analyzing ecosystem responses to land-use change?*
4. *Can trade-offs between intended and unintended consequences of land use be quantified to inform planning and decision-making?*

Sections below provide a roadmap for the organization of the volume in terms of these questions.

2. WHAT ARE THE MAJOR CONSEQUENCES OF LAND-USE CHANGES FOR ECOSYSTEMS AND THEIR ABILITY TO PROVIDE GOODS AND SERVICES IN THE FUTURE?

The primary and overwhelming benefit to society from land-use change is appropriation of ecosystem goods—food, fiber, and timber—for human consumption. Land-use change enhances the proportion of primary productivity for human use [*Rojstaczer et al.,* 2001; *Vitousek et al.,* 1986], and decreases the proportion remaining to perform other ecosystem services[1] such as regulation of floods, climate, and disease and habitat for other species. Land-use change includes both the direct conversion of the land surface and changes in land management to enhance productivity.

Any categorization of ecosystem responses is artificial and masks complex interactions among soil, nutrients, vegetation, the atmosphere, streams, and disease pathogens. For example, deforestation alters stream ecology, which, in turn, alters habitats for disease vectors [*Patz and Norris*, this volume]. Climatic feedbacks alter precipitation patterns [*Avissar et al.*, this volume], which affect runoff and surface hydrology [*Eshleman*, this volume]. However, for the purposes of organizing this volume and with full knowledge that the boundaries are artificial, we categorize the multiple ecosystem responses to land-use change as follows:

- *Hydrologic responses*, including the effects of land-use change on stream flows, flood potential, and sedimentation
- *Climatic responses,* including altered exchanges of water, energy, and momentum between the land surface and atmosphere and the effects on temperature and precipitation
- *Biogeochemical fluxes*, including fluxes of carbon dioxide, nitrous oxide and other greenhouse gases, as well as other trace gases, to the atmosphere and fluxes of nitrogen, phosphorus and other nutrients within soils and to aquatic systems
- *Human health responses*, including changes in habitats for vectors of parasitic diseases such as malaria and onchocerciasis; exposure to dust from land degradation and associated diseases such as encephalitis; mortality and morbidity from urban heat waves; and changes in air quality
- *Biological diversity*, including loss and fragmentation of habitat, and effects of surface fires, logging, and hunting on plant and animal species.

These are the major issues considered in this volume, but they do not encompass the full range of possible ecosystem responses to land-use change. Other important responses include the loss of cultural and spiritual benefits from ecosystems, both for indigenous peoples and others enjoying recreational opportunities [*Ramakrishnan,* 2001]. Exclusion of these issues is not meant to minimize their importance; rather, it reflects the difficulties in quantifying them in comparison to other responses.

Moreover, we recognize that ecosystem responses to land-use change cannot in reality be separate from other factors affecting ecosystems, most notably climate change. Thomson et al. [this volume] point out that disease vectors in West Africa

[1] Ecosystem services are the benefits people obtain from the world's ecosystems, including provisioning services (food, water, timber, fiber, and genetic resources), regulating services (regulation of climate, floods, disease, and water quality), cultural services (recreational, aesthetic, and spiritual benefits), and supporting services (soil formation, photosynthesis and nutrient cycling) [Millennium Ecosystem Assessment, Ecosystems and Human Well-being: A Framework for Assessment. Island Press, Washington, DC, 2003].

are a complicated response to both climate and land use. Laurance [this volume] demonstrates that future biodiversity in the New World tropics will be a combined response to land use and climate change. Nor can ecosystem responses be separated from the driving forces of land-use change, pointed out by Verburg et al. [this volume] in terms of feedbacks between declining soil fertility and land-use decisions in Vietnam.

3. HOW DO ECOSYSTEM RESPONSES VARY WITH TYPE OF LAND-USE CHANGE, STAGE IN THE LAND-USE TRANSITION, AND BIOPHYSICAL SETTING?

The term "land use" encompasses a wide range of human activities on the land surface, from agriculture to dam impoundments to urban uses (see box in *Loveland and DeFries* [this volume] for definitions and *Klein Goldewijk* [this volume] for global distributions of land-use types). Clearly, the type of land-use change determines to a large degree the ecosystem response (Table 1). For example, deforestation for agricultural expansion alters exchanges of energy and water between the land surface and atmosphere [*Bonan*, this volume; *Avissar et al.*, this volume], while agricultural intensification leads to nutrient loading from runoff of synthetic fertilizers [*Foley et al.*, this volume].

By examining the multiple ecosystem responses to land use, we seek to develop a typology of the most common responses. The schematic "land-use transition" (Figure 2) allows us to formulate syndromes of ecosystem responses to land-use change. Similar to the demographic transition in

Table 1. Major types of land-use change, ecosystem responses, and locations of studies considered in Section I of this volume

Land-use change	Ecosystem responses	Location of case studies discussed in Section I of this volume	Chapter
Deforestation for pasture and agricultural expansion	Hydrological responses, e.g., flood potential, base flow, sedimentation	Experimental and modeled watersheds	Eshleman
		Midwestern US	Potter et al.
	Biogeochemical responses, e.g., carbon fluxes to the atmosphere	Global forests	Houghton and Goodale
	Biogeochemical responses, e.g., soil productivity and nutrient fluxes to aquatic systems	Amazon	Davidson et al.
	Climate responses, e.g., changes in albedo, evapotranspiration, atmospheric circulation	Temperate, tropical, and boreal	Bonan
		Amazon	Avissar et al.
	Human health responses, e.g., breeding sites for disease vectors	Global	Patz and Norris
		West Africa	Thomson et al.
	Biodiversity responses, e.g., fragmentation, habitat loss	Amazon	Laurance
Dam impoundments and irrigation	Hydrologic responses, e.g., magnitude of peak floods	Experimental and modeled watersheds	Eshleman
	Human health responses, e.g., breeding habitats for parasitic diseases	Global	Patz and Norris
		West Africa	Thomson et al.
Grazing and land degradation	Human health responses, e.g., meningitis associated with dust	West Africa	Thomson et al.
	Biogeochemical responses, e.g., trace gas fluxes, carbon and nitrogen fluxes	Arid and semi-arid regions	Asner and Martin
Urban and Suburbanization	Biogeochemical responses, e.g., nitrogen emissions to atmosphere and aquatic systems	Colorado Front Range	Baron et al.
		Arid lands of central Arizona	Grimm et al.
	Human health responses, e.g., heat islands, air quality	Global urban areas	Patz and Norris
	Hydrologic responses, e.g., change in flood potential, stream temperature	Cheasapeake Bay watersheds	Moglen et al.
		Experimental and modeled watersheds	Eshleman
Wetland drainage	Hydrologic responses, e.g., susceptibility to floods, soil erosion	Europe and North America	Eshleman
		Midwestern US	Potter

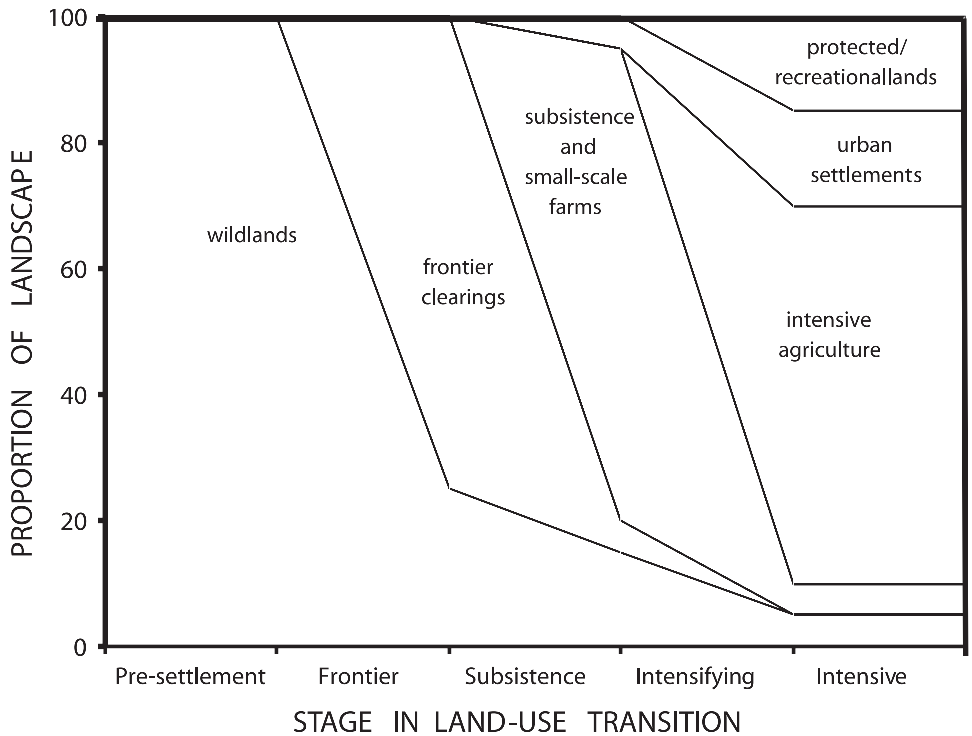


Figure 2. Idealized stages in the land-use transition from frontier clearing to intensive agriculture. Different parts of the world are in different stages of this transition depending on economic and ecological conditions (adapted from *Mustard et al.* [in press]; *DeFries et al.* [2004]).

which countries move from high fertility rates and high death rates to low fertility and death rates, and the associated epidemiological transition in which diseases shift from pandemics and a prevalence of childhood diseases to chronic and degenerative diseases of an aging population [*National Research Council,* 1993], land use potentially follows a series of transitions depending on economic and ecological conditions [*DeFries et al.,* 2004; *Mustard et al.,* in press]. Landscapes might pass through a transition from wildlands to frontier clearing to subsistence agriculture to intensive agriculture and urban areas over a period of years or centuries. If topography, climate, or other ecological conditions are too inhibiting, or if economic conditions do not provide the necessary infrastructure, landscapes might remain in one stage of the transition indefinitely. At the other end of the transition, the later stages of the "forest transition" [*Mather,* 1990] lead to higher yields, less land area in agriculture and greater forest area for recreational uses. These historically observable transitions are not necessarily linear in trajectory and can occur rapidly over a period of years or slowly over centuries.

This volume explores characteristic ecosystems responses according to stage in the land-use transition. The utility of this information for land-use decisions is analogous to the utility of designing public health interventions in a particular place according to its current stage in the epidemiological transition. In any particular situation, which ecosystem responses to land-use decisions are likely to be important? Can ecosystem responses be anticipated, so that trade-offs between provision of ecosystem goods and the consequences for other ecosystem services can be evaluated and factored into decision-making?

Table 2 illustrates typical ecosystem responses to land use in different stages of the transition. Within the stage of frontier clearing, for example, the biogeochemical response is likely to occur from carbon dioxide fluxes released by biomass burning. In the intensive agriculture stage the response will likely occur from nitrous oxide emissions and eutrophication from fertilizer applications.

Ecosystem responses vary not only according to the stage in land-use transition, but also with the biophysical and ecological setting. Bonan [this volume] discusses the cooling effect associated with forest clearing in temperate latitudes and the opposite warming effect in the tropics. Asner and Martin [this volume] illustrate the different effects of overgrazing—desertification or woody encroachment—depend-

Table 2. Characteristic ecosystem responses with stages in land-use transition

Ecosystem response	Stage in transition: Frontier clearings	Subsistence and small-scale agriculture	Intensive agriculture/urban settlements
Biogeochemical	CO_2 emissions from biomass clearing	CH_4 emissions from ruminants; changes in C and N stocks from grazing	N and P nutrient loading to aquatic systems; N_2O emissions to atmosphere from synthetic fertilizer
Human health	Changes in habitats for disease vectors	Zoonotic diseases transmitted from domestic animals; dust-related diseases from land degradation	Urban heat waves; air quality
Biodiversity	Habitat fragmentation and loss	Loss of animal species from overhunting	Loss of stream diversity from nutrient loading and terrestrial diversity from monoculture; increase in recreational protected areas
Hydrological	Changes in stream flows and sediment loading	Sedimentation from soil erosion	Change in flood frequencies from dams, channelization, and impervious surfaces
Climate	Changes in surface roughness and moisture convection from small clearings	Increased albedo from grazing	Changes in energy (albedo) and water (evapotranspiration) fluxes to atmosphere in large agricultural fields; urban heat islands

ing on whether the location is arid or mesic. Grimm et al. [this volume] and Moglen et al. [this volume] portray the hydrological consequences of urbanization, the former in an arid area where stream flashiness is similar in urban and desert streams and the later in the more humid eastern U.S. where urbanization increases peak flows. These examples illustrate the role of both the type of land-use change and the biophysical characteristics in determining the ecosystem response.

4. WHAT ARE THE APPROPRIATE TEMPORAL AND SPATIAL SCALES FOR ANALYZING ECOSYSTEM RESPONSES TO LAND-USE CHANGE?

Ecosystem responses to land-use change occur over a wide range of spatial and temporal scales. The most obvious responses occur on a local spatial scale and short time scale, such as declines in water quality, flooding, or urban heat islands (Figure 3). Because of the tangible and immediate

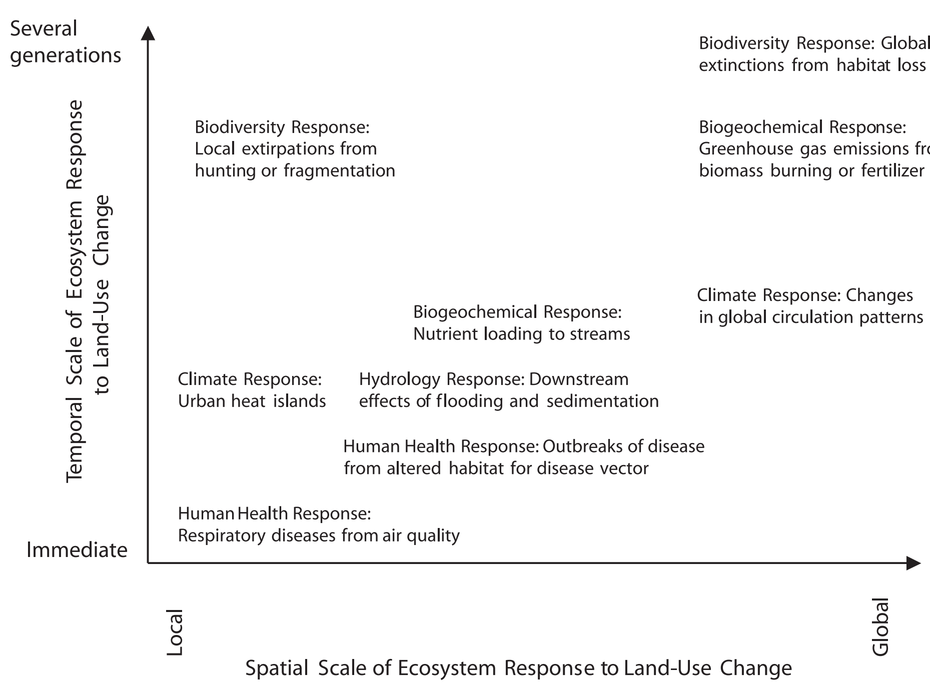
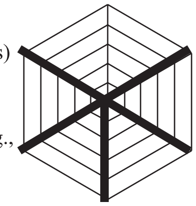


Figure 3. Examples of ecosystem responses to land-use change at different temporal and spatial scales.



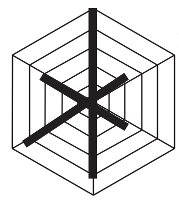


Figure 4. Spider diagram illustrating hypothetical trade-offs between ecosystem goods and ecosystem responses before (top) and after (bottom) land-use change (adapted from *DeFries et al.* [2004]; *DeFries and Pagiola* [in review]).

impact, policies to mitigate these negative consequences are more easily developed and implemented, demonstrated by policy responses to local air and water pollution in the last few decades in many industrialized countries [*Torras and Boyce,* 1998]. When the ecosystem responses are more distant in time or space, such as greenhouse gas emissions and biodiversity loss, policies are more difficult to implement partly because the impacts cannot be quantified as directly [*Speth,* 2004].

Ecosystems are complex and dynamic, so linear responses to land-use change are unlikely. For example, increases in peak streamflow are not directly proportional to the area of forest cleared. Instead, the responses are non-linear, such that small changes in land use generate a large response, or vice versa. Moreover, thresholds are prevalent, such as a crash in a species' population once its regional abundance falls below some critical viable threshold [*Terborgh et al.,* 2001].

Identifying these non-linearities and thresholds is a scientific challenge, but offers the possibility of policy responses that take advantage of "small losses–big gains," whereby a small compromise in immediate societal benefit results in a big gain in ecosystem benefits, or conversely a big gain in social benefit results in only a small loss in ecosystem function [*DeFries et al.,* 2004]. For example, Foley et al. [this volume] document the 20-fold increase in nitrogen fertilizer use in the Mississippi Basin since the mid-1940s and the resulting nitrate flux and hypoxia in the Gulf of Mexico. Yields respond non-linearly to fertilizer use, so that increasing fertilizer use results in only small gains in yield above a certain level [*Donner et al.,* 2002]. Above this point, a decision to apply less fertilizer trades large reductions in nitrate leaching (big ecosystem gain) with small reductions in crop yield (small societal loss). Knowledge of the non-linear relationships and thresholds between land-use change and ecosystem response is key to identifying these opportunities.

5. CAN TRADE-OFFS BETWEEN INTENDED AND UNINTENDED CONSEQUENCES OF LAND USE BE QUANTIFIED TO INFORM PLANNING AND DECISION-MAKING?

Finally, the ultimate objective of this volume is to aid and inform decisions that balance the human needs for ecosystem goods while mitigating the unintended ecosystem responses. In the absence of information on ecosystem responses, it is difficult to take them into account and to weigh the trade-offs. To the extent that the ecosystem responses can be identified, it becomes possible to analyze the trade-offs. In reality, the ability to quantify the ecosystem responses and reduce them to commensurate units is fraught with uncertainties, but a conceptual structure such as the spider diagrams in Figure 4 is useful for understanding responses and possible trade-offs between immediate gains in ecosystem

Table 3. Regional integrated analyses of ecosystem responses to land-use change in Section III of this volume

Region	Stage in land-use transition	Major type of land-use change	Major ecosystem response discussed	Chapter
Mississippi Basin	Intensive agriculture	Increasing fertilizer application; decreasing cropland area	Declining water quality	Foley et al.
Chesapeake Bay Watershed	Intensive agriculture/urban and suburban expansion	Ex-urban sprawl	Declining water quality in streams	Goetz et al.
Southern Yucatán Peninsular Region	Subsistence and small-scale agriculture	Expanding small-scale agriculture	Fragmentation; invasive species	Lawrence et al.
Eurasian Rangeland	Subsistence grazing	Nomadic pastoralism to sedentary agriculture	Grassland degradation	Ojima et al.
Rural China	Subsistence and small-scale agriculture	Increasing use of chemical fertilizer; increasing tree cover	Increasing nutrient loading and atmospheric N_2O emissions; carbon sequestration	Ellis
Amazonia	Frontier clearing	Clearing primary forest for logging, ranching, and agriculture	Atmospheric CO_2 emissions; climate responses from changes in energy balance and particulates from fires	Keller et al.

goods from land-use change and longer term ecosystem responses. Explicit assumptions about the time and space scales are key to highlighting possible trade-offs and revealing hidden assumptions [*DeFries et al.,* in review].

The chapters that follow in this volume synthesize the state-of-knowledge on ecosystem responses to land-use change and apply this knowledge in many places around the world. We view this effort as a first step towards a framework and analytical structure for understanding and communicating the interactions between land use, people's needs and livelihoods, and ecosystems.

6. ORGANIZATION OF THIS VOLUME

Section I of this volume addresses each of the major ecosystems' responses to land-use change, including hydrological, climatic, biogeochemical, human health, and biodiversity responses. For each type of response, the chapters provide an overview of the science and at least one case study in a particular location.

Although the major focus of this volume is ecosystem responses, no volume on land-use change would be complete without the other two components of land change science (Figure 1). Section II: Observing, Forecasting, and Hindcasting Land-Use Change includes projections of future land-use change within a modeling framework that accounts for socioeconomic, demographic, and technological drivers (why does land-use change occur?), and a historical overview of land-use change and analysis of capabilities to monitor land cover change primarily with satellite data (where is land-use change occurring?).

Finally, the goal of understanding ecosystem responses to land-use change is to inform decisions at local, national, regional, and international scales, requiring analysis of the multiple ecosystem responses and the trade-offs. Section III: Regional Case Studies of Ecosystem Interactions With Land-Use Change includes chapters that address multiple ecosystem responses in different regions around the world. The regions span the stages in the land-use transition and address different types of land-use change (Table 3). The regions range from long-settled village landscapes in rural China to frontier clearing of primary forest in the Amazon to suburban landscapes in the Chesapeake Bay watershed in the eastern United States. These integrated analyses illustrate the particular socioeconomic and ecological conditions present at the regional scale, and the need for land-use decisions to consider these conditions.

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