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DYNAMICS OF LAND-USE AND LAND-COVER CHANGE IN TROPICAL REGIONS

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■ **Abstract** We highlight the complexity of land-use/cover change and propose a framework for a more general understanding of the issue, with emphasis on tropical regions. The review summarizes recent estimates on changes in cropland, agricultural intensification, tropical deforestation, pasture expansion, and urbanization and identifies the still unmeasured land-cover changes. Climate-driven land-cover modifications interact with land-use changes. Land-use change is driven by synergetic factor combinations of resource scarcity leading to an increase in the pressure of production on resources, changing opportunities created by markets, outside policy intervention, loss of adaptive capacity, and changes in social organization and attitudes. The changes in ecosystem goods and services that result from land-use change feed back on the drivers of land-use change. A restricted set of dominant pathways of land-use change is identified. Land-use change can be understood using the concepts of complex adaptive systems and transitions. Integrated, place-based research on land-use/land-cover change requires a combination of the agent-based systems and narrative perspectives of understanding. We argue in this paper that a systematic analysis of local-scale land-use change studies, conducted over a range of timescales, helps to uncover general principles that provide an explanation and prediction of new land-use changes.

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INTRODUCTION

Concerns about land-use/cover change emerged in the research agenda on global environmental change several decades ago with the realization that land surface processes influence climate. In the mid-1970s, it was recognized that land-cover change modifies surface albedo and thus surface-atmosphere energy exchanges, which have an impact on regional climate (1–3). In the early 1980s, terrestrial ecosystems as sources and sinks of carbon were highlighted; this underscored the impact of land-use/cover change on the global climate via the carbon cycle (4, 5). Decreasing the uncertainty of these terrestrial sources and sinks of carbon remains a serious challenge today. Later, the important contribution of local evapotranspiration to the water cycle—that is precipitation recycling—as a function of land cover highlighted yet another considerable impact of land-use/cover change on climate, at a local to regional scale in this case (6).

A much broader range of impacts of land-use/cover change on ecosystem goods and services were further identified. Of primary concern are impacts on biotic diversity worldwide (7), soil degradation (8), and the ability of biological systems to support human needs (9). Land-use/cover changes also determine, in part, the vulnerability of places and people to climatic, economic, or sociopolitical perturbations (10). When aggregated globally, land-use/cover changes significantly affect central aspects of earth system functioning. All impacts are not negative though, as many forms of land-use/cover changes are associated with continuing increases in food and fiber production, in resource use efficiency, and in wealth and well-being.

Understanding and predicting the impact of surface processes on climate required long-term historical reconstructions and projections into the future of land-cover changes at regional to global scales (11, 12). Quantifying the contribution of terrestrial ecosystems to global carbon pools and flux required accurate mapping of land cover and measurements of land-cover conversions worldwide (13–15). Fine resolution, spatially explicit data on landscape fragmentation were required to understand the impact of land-use/cover changes on biodiversity (16, 17). Predicting how land-use changes affect land degradation, the feedback on livelihood strategies from land degradation, and the vulnerability of places and people in the face of land-use/cover changes requires a good understanding of the dynamic human-environment interactions associated with land-use change (10).

Over the last few decades, numerous researchers have improved measurements of land-cover change, the understanding of the causes of land-use change, and predictive models of land-use/cover change, in part under the auspices of the Land-Use and Land-Cover Change (LUCC) project of the International Geosphere-Biosphere Programme (IGBP) and International Human Dimensions Programme on Global Environmental Change (IHDP) (18, 19). Many scientists, especially in the natural sciences, previously assumed that generating local- to global-scale projections of land change several centuries into the past and about 100 years into the future would be easy. Actually, many thought land changes consisted mostly in the conversion of pristine forests to agricultural uses (deforestation) or the destruction of natural vegetation by overgrazing, which leads to desert conditions (desertification). These conversions were assumed to be irreversible and spatially homogeneous and to progress linearly. Only the growth of the local population and, to a lesser extent, its increase in consumption were thought to drive the changes in land conditions.

Recent research has largely dispelled these simplifications and replaced them by a representation of much more complex, and sometimes intricate, processes of land-use/cover change. A consensus is progressively being reached on the rate and location of some of the main land changes, but other forms of change, such as desertification, are still unmeasured and controversial. Understanding of the causes of land-use change has moved from simplistic representations of two or three driving forces to a much more profound understanding that involves situation-specific interactions among a large number of factors at different spatial and temporal scales. The richness of explanations has greatly increased, often at the expense of generality of the explanations. Today, only a very few models of land-use change can generate long-term, realistic projections of future land-use/cover changes at regional to global scales. The last decade, however, has witnessed innovative methodological developments in the modeling of land-use change at local to regional scales (20–22). Nevertheless, the recent progress in our understanding of the causes of land-use change still has to be fully integrated in models of the process.

This review describes how our understanding of land-use/cover change has moved from simplicity to greater realism and complexity over the last decades. The main emphasis of the review is on tropical regions. Our goal is to extract from this complexity a general framework for a more general understanding of land-use/cover change. First, the most recent estimates of the magnitude of land-use/cover change are summarized. Second, the complex nature of land-cover change is discussed to emphasize the need to integrate all scales and processes of change. Third, a synthesis of recent case study evidence on the causes of land-use change is presented, with emphasis on the mode of interaction between diverse causes and dominant pathways of change. Fourth, the complexity of land-use change is described using the notions of complex adaptive systems and transition. Integrative perspectives to analyze land-use/cover changes are then discussed. The review highlights the dynamic nature of coupled human-environment systems in relation to land-use/cover change.

RECENT ESTIMATES OF GLOBAL LAND-USE/COVER CHANGE

Historical Changes

Since humans have controlled fire and domesticated plants and animals, they have cleared forests to wring higher value from the land. About half of the ice-free land surface has been converted or substantially modified by human activities over the last 10,000 years. A recent study estimated that undisturbed (or wilderness) areas represent 46% of the earth's land surface (23). Forests covered about 50% of the earth's land area 8000 years ago, as opposed to 30% today (24). Agriculture has expanded into forests, savannas, and steppes in all parts of the world to meet the demand for food and fiber. Agricultural expansion has shifted between regions over time; this followed the general development of civilizations, economies, and increasing populations (25).

Two recent studies estimated historical changes in permanent cropland at a global scale during the last 300 years by spatializing historical cropland inventory data based on a global land-cover classification derived by remote sensing, which used a hindcasting approach (11), or based on historical population density data (26). The area of cropland has increased globally from an estimated 300–400 million ha in 1700 to 1500–1800 million ha in 1990, a 4.5- to fivefold increase in three centuries and a 50% net increase just in the twentieth century. The area under pasture—for which more uncertainties remain—increased from around 500 million ha in 1700 to around 3100 million ha in 1990 (27). These increases led to the clearing of forests and the transformation of natural grasslands, steppes, and savannas. Forest area decreased from 5000–6200 million ha in 1700 to 4300–5300 million ha in 1990. Steppes, savannas, and grasslands also experienced a rapid decline, from around 3200 million ha in 1700 to 1800–2700 million ha in 1990 (11, 26) (Table 1).

Europe, the Indo-Gangetic Plain, and eastern China experienced first the most rapid cropland expansion during the eighteenth century. Starting in the nineteenth century, the newly developed regions of North America and the former Soviet Union followed suit. China experienced a steady rate of expansion throughout the last three centuries (28). A very gradual cropland expansion occurred in Africa, south and Southeast Asia, Latin America, and Australia until 1850, but since then,

TABLE 1 Historical changes in land use/cover at a global scale over the last 300 years (11, 26, 27)

	Forest/woodland (10^6 ha)	**Steppe/savanna/grassland (10^6 ha)**	**Cropland (10^6 ha)**	**Pasture (10^6 ha)**
1700	5000 to 6200	3200	300 to 400	400 to 500
1990	4300 to 5300	1800 to 2700	1500 to 1800	3100 to 3300

these regions have experienced dramatic increases in cropland, especially during the second half of the twentieth century. The greatest cropland expansion in the twentieth century occurred in south and Southeast Asia (28). The Corn Belt in the United States, the prairie provinces in Canada, the pampas grassland region in Argentina, and, a few decades later, southeast Brazil have also seen rapid expansion of permanent cropland early in the twentieth century (28).

Most Rapid Land-Cover Changes of the Last Decades

RECENT FOREST-COVER CHANGES Deforestation occurs when forest is converted to another land cover or when the tree canopy cover falls below a minimum percentage threshold—10% for the United Nations (U.N.) Food and Agriculture Organization (F.A.O.) (29). On the basis of national statistics, inventory reports, estimates by experts, and a pantropical remote sensing survey for tropical forests only, the Global Forest Resources Assessment 2000 (29) estimated that the world's natural forests decreased by 16.1 million hectares per year on average during the 1990s; that is a loss of 4.2% of the natural forest that existed in 1990. However, some natural forests were converted to forest plantations. Gains in forest cover arose from afforestation on land previously under nonforest land use (1.6 million hectares per year globally) and the expansion of natural forests in areas previously under agriculture, mostly in western Europe and eastern North America (3.6 million hectares per year globally). The net global decrease in forest area was therefore 9.4 million hectares per year from 1990 to 2000 (29). The total net forest change for the temperate regions was positive, but it was negative for the tropical regions.

FAO estimated that tropical regions lost 15.2 million hectares of forests per year during the 1990s. Recent estimates for only the world's humid tropical forests (30), based on a sampling strategy of remote sensing data, revised downward by 23% FAO's net rate of change in forest cover for the humid tropics, which exclude tropical dry forests. According to Achard et al. (30), between 1990 and 1997, 5.8 ± 1.4 million hectares of humid tropical forest were lost each year (Table 2). Forest regrowth accounted for 1.0 ± 0.32 million hectares. The annual rate of net cover change in humid tropical forest was 0.43% during that period. A further 2.3 ± 0.7 million hectares of forest were visibly degraded. This figure does not include forests affected by selective logging. Southeast Asia has experienced the highest

TABLE 2 Mean annual change estimates of humid tropical forest cover during the 1990–1997 period[a]

	Forest cover in 1990 (10^6 ha)	Annual net cover change		Annual deforestation		Annual forest regrowth		Annual forest degradation	
		10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%
Latin America	669 ± 57	−2.2 ± 1.2	0.33	2.5 ± 1.4	0.38	0.28 ± 0.22	0.04	0.83 ± 0.67	0.13
Africa	198 ± 13	−0.71 ± 0.31	0.36	0.85 ± 0.30	0.43	0.14 ± 0.11	0.07	0.39 ± 0.19	0.21
Southeast Asia	283 ± 31	−2.0 ± 0.8	0.71	2.5 ± 0.8	0.91	0.53 ± 0.25	0.19	1.1 ± 0.44	0.42
Global	1150 ± 54	−4.9 ± 1.3	0.43	5.8 ± 1.4	0.52	1.0 ± 0.32	0.08	2.3 ± 0.71	0.2

[a]Abstracted with permission from Achard F, Eva HD, Stibig HJ, Mayaux P, Gallego J, et al. 2002. Determination of deforestation rates of the world's humid tropical forests. *Science* 297:999–1002. Copyright 2002 American Association for the Advancement of Science, http://www.sciencemag.org.

rate of net cover change (0.71% per year), whereas Africa and Latin America present lower rates (respectively 0.36% and 0.33%). Latin America, however, lost about the same area of forest as Southeast Asia during the 1990–1997 time period (30). Forest degradation was most extensive in Southeast Asia (0.42% per year), lowest in Latin America (0.13% per year), and intermediate in Africa (0.21% per year). Forest regrowth was more extensive, both in absolute and relative terms, in Southeast Asia than in the other humid tropical regions (0.19% for Southeast Asia, 0.04% for Latin America, and 0.07% for Africa) (30).

These recent assessments of deforestation, as well as another remote sensing survey at a coarser spatial resolution but covering the entire tropical belt (31), concur to estimate less deforestation in the 1990s than was observed in the 1980s. Still, it is unlikely that deforestation has significantly slowed down, because differences in methods of assessment and definitions used may account for at least part of the difference (32). Moreover, deforestation in the dry tropical forests may often be underestimated.

In Latin America, large-scale forest conversion and colonization for livestock-based agriculture is prevalent, whereas cropland expansion by smallholders dominates in Africa. In Asia, intensified shifting agriculture, including migration into new areas, gradual change of existing areas toward more permanent agriculture, and logging explain most of the deforestation (29, 30, 33). Within these regions, deforestation is largely confined to a few areas undergoing rapid change, with annual rates of deforestation from 2% to 5% (Figure 1). The largest deforestation front is the *arc of deforestation* of the Brazilian Amazon, which extends more recently outside Brazil, east of the Andes, and along the road from Manaus to Venezuela. More scattered areas of forest loss are detected in the Chaco and Atlantic forest areas in South America. Central America has significant deforestation fronts in the Yucatán and at the Nicaraguan border with Honduras and Costa Rica. In Africa, forest-cover change is very rapid in Madagascar, Côte d'Ivoire, and the Congo basin, in small scattered hot spots. In Southeast Asia several deforestation fronts are found around Sumatra, Borneo, Vietnam, Cambodia, and Myanmar.

RECENT CHANGES IN AGRICULTURAL AREAS Historically, humans have increased agricultural output mainly by bringing more land into production. The greatest concentration of farmland is found in Eastern Europe, with more than half of its land area in crop cover (28). In the United Kingdom, about 70% of its area is classified as agricultural land (cropland, grassland/rough grazing), with agriculture and areas set aside for conservation or recreation intimately intertwined (37). Despite claims to the contrary, the amount of suitable land remaining for crops is very limited in most developing countries (38, 39), where most of the growing food demand originates. Where there is a large surplus of cultivable land, land is often under rain forest or in marginal areas (38, 39).

The period after 1960 has witnessed a decoupling between food production increase and cropland expansion (Table 3). The 1.97-fold increase in world food production from 1961 to 1996 was associated with only a 10% increase of land under cultivation but also with a 1.68-fold increase in the amount of irrigated cropland and a 6.87- and 3.48-fold increase in the global annual rate of nitrogen and phosphorus fertilization (40). In 2000, 271 million ha were irrigated (25). Globally, the cropland area per capita decreased by more than half in the twentieth century, from around 0.75 ha per person in 1900 to only 0.35 hectare per person in 1990 (28). Note, however, that national statistics in developing countries often substantially underreport agricultural land area (28, 38), e.g., by as much as 50% in parts of China (41).

The mix of cropland expansion and agricultural intensification has varied geographically (25). Tropical Asia increased its food production mainly by increasing

TABLE 3 Increase in world food production and agricultural inputs from 1961 to 1996, based on FAO data (40)

	Number-fold increase in 35 years (1961–1996)
World food production	1.97
Land under cultivation	1.098
Proportion of irrigated land	1.68
Nitrogen fertilization	6.87
Phosphorus fertilization	3.48

fertilizer use and irrigation. Most of Africa and Latin America increased their food production through both agricultural intensification and extensification. Western Africa is the only part of the world where, overall, cropland expansion was accompanied by a decrease in fertilizer use (−1.83% per year) and just a slight increase in irrigation (0.31% per year compared to a world average of 1.22% per year). In 1995, the global irrigated areas were distributed as 68% in Asia, 16% in the Americas, 10% in Europe, 5% in Africa, and 1% in Australia (42). In western Europe and the northeastern United States, cropland decreased during the last decades, after abandonment of agriculture or, in a few cases, following land degradation mostly on marginal land. Globally, this change has freed 222 million ha from agricultural use since 1900 (28).

RECENT CHANGES IN PASTORAL AREAS Natural vegetation covers have given way not only to cropland but also to *pasture*—defined as land used permanently for herbaceous forage crops, either cultivated or growing wild (25). The distinction between pasture and natural savannas or steppes is not always clear. Most pastures are located in Asia (33%) and Africa (28%), with only a small portion being located in Europe and North America (7%) (25). During the last decade, pastures increased considerably in nontropical Asia (at an annual rate of 4.78%), whereas data suggest that pasture land has apparently decreased in eastern Africa. As eastern Africa recorded a large increase in head of cattle over this period [872,000 additional head of cattle per year between 1992 and 1999, according to FAO (25)], it is likely that many areas in pastoral use in Africa are classified as natural vegetation.

RECENT CHANGES IN URBANIZATION In 2000, towns and cities sheltered more than 2.9 billion people, nearly half of the world population (43). Urban population has been growing more rapidly than rural population worldwide, particularly in developing countries. According to the U.N. Population Division (43), the number of megacities, defined here as cities with more than 10 million inhabitants, has changed from one in 1950 (New York) to 17 in 2000, the majority of which are in developing countries. Urban form and function have also changed rapidly. Built-up or paved-over areas are roughly estimated to occupy from 2% to 3% of the earth's land surface (38, 44). For example, in 1997, the 7 million inhabitants of Hong Kong were supported on as little as 120 km^2 of built-up land (45). However, urbanization affects land in rural areas through the *ecological footprint* of cities. This footprint includes, but is not restricted to, the consumption of prime agricultural land in peri-urban areas for residential, infrastructure, and amenity uses, which blurs the distinction between cities and countryside, especially in western developed countries. Urban inhabitants within the Baltic Sea drainage, for example, depend on forest, agriculture, wetland, lake, and marine systems that constitute an area about 1000 times larger than that of the urban area proper (46). In 1997, total nonfood material resources consumed in Hong Kong (i.e., its urban material metabolism) were nearly 25 times larger than the total material turnover of the natural ecosystem. Fossil fuel energy consumed in this city (i.e., its urban energy metabolism) exceeded photosynthetically fixed solar energy by 17 times (45). Time series of global maps of nighttime lights detected by satellite (47) illustrate the rapid changes in both urban extent and electrification of the cities and their surroundings. A question still being debated is whether urban land use is more efficient than rural land use and, therefore, whether urbanization saves land for nature.

The most populated clusters of cities are mainly located along the coastal zones and major waterways—in India, East Asia, on the eastern U.S. coast, and in western Europe (Figure 2). The cities experiencing the most rapid change in urban population between 1990 and 2000 are mostly located in developing countries (48) (Figure 2). It is estimated that 1 to 2 million ha of cropland are being taken out of production every year in developing countries to meet the land demand for housing, industry, infrastructure, and recreation (39). This is likely to take place mostly on prime agricultural land located in coastal plains and in river valleys. Note that rural households may consume more land per capita for residential purposes than their urban counterparts (39).

The Still Unmeasured Land-Cover Changes

Other forms of rapid land-cover change that are thought to be widespread are still poorly documented at the global scale. Local- to national-scale studies, however, demonstrate their importance and ecological significance. Prominent among these are changes in the (sub)tropical dry forests (e.g., Miombo forests in southern Africa and Chaco forests in South America); forest-cover changes caused by selective logging, fires, and insect damage; drainage or other forms of alteration of wetlands; soil degradation in croplands; changes in the extent and productive capacity of pastoral lands; and dryland degradation, also referred to as desertification, which remains a controversial issue.

THE COMPLEX NATURE OF LAND-COVER CHANGES

Conversion Versus Modification in Land Cover

The land cover is defined by the attributes of the earth's land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human structures. Data sets used in land-use/cover change research represent the land surface by a set of spatial units, each associated with attributes. These attributes are either a single land-cover category (i.e., leading to a discrete representation of land cover) (49) or a set of values for continuous biophysical variables (i.e., leading to a continuous representation of land cover) (50). The discrete representation of land cover has the advantages of concision and clarity, but it has led to an overemphasis of land-cover conversions and a neglect of land-cover modifications. *Land-cover conversions* (i.e., the complete replacement of one cover type by another) are measured by a shift from one land-cover category to another, as is the case in agricultural expansion, deforestation, or change in urban extent. *Land-cover modifications* are more subtle changes that affect the character of the land cover without changing its overall classification.

Recently, there has been increased recognition of the importance of the processes of modification of land attributes. For example, mostly *agricultural intensification*—defined as higher levels of inputs and increased output of cultivated or reared products per unit area and time—permitted an increase in the world's food production over the last decades (40). Thanks to the use of high-yielding crop varieties, fertilization, irrigation, and pesticides on land already under agriculture, crop yield increases have outpaced global human population growth (51). In the Brazilian Amazon, every year forest impoverishment caused by selective logging and fires affects an area at least as large as the area affected by forest-cover conversion (52). The expansion of woody shrubs in the western United States grasslands, following fire suppression and overgrazing, contributed to a large carbon sink (14, 53). The severity of soil erosion and its impact on associated resources in the United States has been debated because of discrepancies between estimates based on models and observed sediment budgets (8). Declines in tree density and species richness in the last half of the twentieth century were measured in a region of Senegal, in the West African Sahel, and provided evidence of desertification in that region (54). Another study in western Sudan, a region that was allegedly affected by desertification, did not find any decline in the abundance of trees despite several decades of droughts (55).

The monitoring of land-cover conversion can be performed by a simple comparison of successive land-cover maps. By contrast, the detection of subtle changes within land-cover classes—that is modifications—requires a representation of land cover where the surface attributes vary continuously in space and time, at the seasonal and interannual scales (50, 56). This representation allows detection of, for example, changes in tree density, in net primary productivity, or in the length of the growing season. Earth observation from satellite sensors provides repetitive and spatially explicit measurements of biophysical surface attributes, such as vegetation cover, biomass, vegetation community structure, surface moisture, superficial soil organic matter content, and landscape heterogeneity.

Analyses of multiyear time series of these attributes, their fine-scale spatial pattern, and their seasonal evolution have led to a broader view of land-cover change. Remote sensing data highlight high temporal frequency land-cover modifications of great importance for earth system processes. In particular, data from wide-field-of-view satellite sensors reveal patterns of seasonal and interannual variations in land surface attributes that are driven not by land-use change but rather by climatic variability. These variations include the impact on vegetation and surface moisture of the El Niño Southern Oscillation (ENSO) phenomena (57–59), natural disasters such as floods and droughts (60, 61), changes in the length of the growing season in boreal regions (62), and changes in vegetation productivity due to erratic rainfall fluctuations in the African Sahel, which lead to an expansion and contraction of the Sahara (63).

A study linking coarse resolution remote sensing data with rainfall data tested whether there was a decadal trend in the rain-use efficiency of the African Sahel region. It revealed the absence of widespread subcontinental-scale dryland degradation, although some areas did show signs of degradation (64). These results suggested that the resilience of the Sahel in primary production per unit rainfall has not changed despite serious droughts in the 1970s and 1980s. The impact of fires on land cover has also been well documented with remote sensing data (65), both for the mostly anthropogenic fires in tropical regions (66) and the mostly natural fires in boreal regions (67). Fires result from a combination of climatic factors, which determine fuel availability, fuel flammability, and ignition by lightning, and factors related to land-use/cover change that control fire propagation in the landscape and human ignition.

A combination of coarse and fine spatial resolution satellite sensors allowed measuring at the global scale land-cover changes caused by land-use change, such as deforestation in the humid tropics (30, 31) and change in nighttime city lights, which is a proxy for changes in urban extent and electrification (47). Although numerous local scale studies have mapped and quantified land-cover change with fine resolution remote sensing data, and there are a few subnational- to national-scale studies (35), there are remarkably few such studies at the regional to global scales. National-scale forest inventory and agricultural census data have also been analyzed, in some cases with remote sensing data, to refine estimates of rates and geographic patterns of change in forest cover and cropland (11, 14). Overall, the quantification of areas of rapid land-cover change still suffers from large uncertainties (36).

Progressive Versus Episodic Land-Cover Changes

Time series of remote sensing data reveal that land-cover changes do not always occur in a progressive and gradual way, but they may show periods of rapid and abrupt change followed either by a quick recovery of ecosystems or by a nonequilibrium trajectory. Such short-term changes, often caused by the interaction of climatic and land-use factors, have an important impact on ecosystem processes. For example, droughts in the African Sahel and their effects on vegetation are reinforced at the decadal timescale through a feedback mechanism that involves land surface changes caused by the initial decrease in rainfall (68). Grazing and conversion of semiarid grasslands to row-crop agriculture are the source of another positive desertification feedback by increasing heterogeneity of soil resources in space and time (69). The role of the Amazonian forest as a carbon sink (in natural forests) and source (from land-use changes and fires) varies from year to year as a result of interactive effects between deforestation, abandonment of agricultural land reverting to forests, fires, and interannual climatic variability (70, 71). In Indonesia, periodic El Niño-driven droughts lead to an increase in the forest's susceptibility to fires. Accidental fires are more likely under these conditions and lead to the devastation of large tracts of forests (72) and to the release of huge amounts of carbon from peatland fires (73). Large landholders also seize the opportunity of drought conditions to burn large tracts of forest to convert them to plantations. Forests that have been affected by forest fragmentation, selective logging, or a first fire subsequently become even more vulnerable to fires as these factors interact synergistically with drought (72, 74).

In summary, both land-cover modifications and rapid land-cover changes need to be better taken into account in land-cover change studies. Climate-driven land-cover modifications do interact with land-use changes. Slow and localized land-cover conversion takes place against a background of high temporal frequency regional-scale fluctuations in land-cover conditions caused by climatic variability, and it is often linked through positive feedback with land-cover modifications. These multiple spatial and temporal scales of change, with interactions between climate-driven and anthropogenic changes, are a significant source of complexity in the assessment of land-cover changes. It is not surprising that the land-cover changes for which the best data exist—deforestation, changes in the extent of cultivated lands, and urbanization—are processes of conversion that are not strongly affected by interannual climatic variability. By contrast, few quantitative data exist at the global scale for processes of land-cover modification that are heavily influenced by interannual climatic fluctuations, e.g., desertification, forest degradation and rangeland modifications.

EMPIRICAL EVIDENCE ON THE CAUSES OF LAND-USE CHANGE

Proximate Versus Underlying Causes

Land use is defined by the purposes for which humans exploit the land cover. There is high variability in time and space in biophysical environments, socio-economic activities, and cultural contexts that are associated with land-use change. Identifying the causes of land-use change requires an understanding of how people make land-use decisions and how various factors interact in specific contexts to influence decision making on land use. Decision making is influenced by factors at the local, regional, or global scale. Proximate (or direct) causes of land-use change constitute human activities or immediate actions that originate from intended land use and directly affect land cover (75). They involve a physical action on land cover. Underlying (or indirect or root) causes are fundamental forces that underpin the more proximate causes of land-cover change. They operate more diffusely (i.e., from a distance), often by altering one or more proximate causes (76). Underlying causes are formed by a complex of social, political, economic, demographic, technological, cultural, and biophysical variables that constitute initial conditions in the human-environment relations and are structural (or systemic) in nature (33, 77, 78).

Proximate causes generally operate at the local level (individual farms, households, or communities). By contrast, underlying causes may originate from the regional (districts, provinces, or country) or even global levels, with complex interplays between levels of organization. Underlying causes are often exogenous to the local communities managing land and are thus uncontrollable by these communities. Only some local-scale factors are endogenous to decision makers. An important system property associated with changes in land use is feedback that can either accentuate or amplify the speed, intensity, or mode of land change, or constitute human mitigating forces, for example via institutional actions that dampen, impede, or counteract factors or their impacts. Examples are the direct regulation of access to land resources, market adjustments, or informal social regulations (e.g., shared norms and values that give rise to shared land management practices).

Place-based research followed by systematic comparative analyses of case studies of land-use dynamics have helped to improve understanding of the causes of land-use change (10, 33, 79–83). These syntheses produced general insights on sectoral causes of land-use change and on the mode of interaction between various causes. They identified dominant pathways—also referred to as spirals, trajectories, or syndromes—leading to specific types of change. What has been lacking so far is the development of an integrative framework that would provide a unifying theory for these insights and pathways of land-use change and a more process-oriented understanding of how multiple macrostructural variables interact to affect micro agency with respect to land.

General Insights on Sectoral Causes of Land-Use Change

MULTIPLE CAUSES Land-use change is always caused by multiple interacting factors originating from different levels of organization of the coupled human-environment systems. The mix of driving forces of land-use change varies in time and space, according to specific human-environment conditions. Driving forces can be slow variables, with long turnover times, which determine the boundaries of sustainability and collectively govern the land use trajectory (such as the spread of salinity in irrigation schemes or declining infant mortality), or fast variables, with short turnover times (such as food aid or climatic variability associated with El Niño oscillation). Biophysical drivers may be as important as human drivers. The former define the natural capacity or predisposing conditions for land-use changes. The set of abiotic and biotic factors that determine this natural capacity varies among localities and regions. Trigger events, whether these are biophysical (a drought or hurricane) or socioeconomic (a war or economic crisis), also drive land-use changes. Changes are generally driven by a combination of factors that work gradually and factors that happen intermittently (82).

NATURAL VARIABILITY Natural environmental change and variability interact with human causes of land-use change. Highly variable ecosystem conditions driven by climatic variations amplify the pressures arising from high demands on land resources, especially under dry to sub-humid climatic conditions. Natural and socioeconomic changes may operate as synchronous but independent events. In the Iberian Peninsula during the sixteenth and seventeenth centuries, the peak of the Little Ice Age occurred almost simultaneously with large-scale clearing for cultivated land following the consolidation of Christian rule over the region. This cultivation triggered changes in surface hydrology and significant soil erosion (84). Natural variability may also lead to socioeconomic unsustainability, for example when unusually wet conditions alter the perception of drought risks and generate overstocking on rangelands. When drier conditions return, the livestock management practices are ill adapted and cause land degradation. This overstocking happened several times in Australia and, in the 1970s, in the African Sahel (84). Land-use change, such as cropland expansion in drylands, may also increase the vulnerability of human-environment systems to climatic fluctuations and thereby trigger land degradation.

ECONOMIC AND TECHNOLOGICAL FACTORS Available case studies highlight that, at the timescale of a couple of decades or less, land-use changes mostly result from individual and social responses to changing economic conditions, which are mediated by institutional factors. Opportunities and constraints for new land uses are created by markets and policies and are increasingly influenced by global factors (82, 85). Economic factors and policies define a range of variables that have a direct impact on the decision making by land managers, e.g., input and output prices, taxes, subsidies, production and transportation costs, capital flows and investments, credit access, trade, and technology (86). Internal consumption affects land less than external demand, so subsistence croplands consequently decrease while land under crops for markets increases with a parallel increase in agricultural intensity (87). Market access is largely conditioned by state investments in transportation infrastructure. The unequal distribution of wealth between households, countries, and regions determines geographic differences in economic opportunities and constraints. It affects, for example, who is able to develop, use, and profit from new technologies that increase efficiency in land management.

Improving agricultural technology—as much as providing secure land tenure and giving farmers better access to credit and markets—can potentially encourage more deforestation rather than relieving pressure on the forests (88). The differing impact of agricultural development on forest conversion depends on how the new technologies affect the labor market and migration, whether the crops are sold locally or globally, how profitable farming is at the forest frontier, as well as on the capital and labor intensity of the new technologies (88).

DEMOGRAPHIC FACTORS At longer timescales, both increases and decreases of a given population also have a large impact on land use. Demographic change does not only imply the shift from high to low rates of fertility and mortality (as suggested by the demographic transition), but it is also associated with the development of households and features of their life cycle. The family or life-cycle features relate mainly to labor availability at the level of households, which is linked to migration, urbanization, and the breakdown of extended families into several nuclear families. As an example of the latter phenomenon, the splintering of family herds in the West African Sudan-Sahel zone over the past 25 years—due to increases in nuclear households and the transfer of livestock wealth from herding families to merchants, agriculturalists, and government officials—led to increased investment in crop production, reduced labor availability among pastoral households, lower energy and skills applied to livestock husbandry, and reduced livestock mobility, which increased the risk of land degradation (89). Fuelwood demand by households in Africa differs between nuclear family units and larger consuming units; the latter are generally more energy efficient. Small consuming units thus cause more forest degradation, especially in peri-urban environments (90).

The internal dynamics of traditional and colonist families in humid forest frontiers in South America, which are mainly related to households' capital and labor constraints, explain the microlevel dynamics of land-cover modification by forest types (91), land quality (92), and gender division, as well as the changing social context of deforestation in the Amazon Basin (93–95). Forest clearing is caused by a variety of actors, with differing effects: recent in-migrants practice slash-and-burn agriculture; their children's families shift to fallow agriculture; long-settled families have diversified production; small families have crop/livestock combinations (associated with high rates of forest losses); large families have perennial production modes (associated with low rates of forest losses); and small ranchers are displaced by large ranchers, and upland croppers are displaced by lowland ranchers (96–99).

Life-cycle features arise from and affect rural as well as urban environments. They result from households' strategic responses to both economic opportunities (for example, market signals indicating higher crop profitability) and constraints (due to economic crisis conditions, for example). They shape the trajectory of land-use change, which itself affects the household's economic status (100, 101). Therefore, a population analysis of great nuances is required.

Migration in its various forms is the most important demographic factor causing land-use change at timescales of a couple of decades (33, 102). Migration operates as a significant driver with other nondemographic factors, such as government policies, changes in consumption patterns, economic integration, and globalization (87). Some policies resulting in land-use change either provoke (87) or are intricately linked with (103) increased migration.

The growth of urban aspirations, the urban-rural population distribution, and the impact of rapidly growing cities on ecosystem goods and services are likely to become dominant factors in land-use change in the decades to come, be it in major urban or peri-urban areas (87) or in remote hinterland or watershed areas (96, 104–106). Many new urban dwellers in developing countries still own rural landholdings (107). Although the growth of urban areas creates new local and regional markets for livestock, timber, and agricultural products, it also increases urban remittances to the countryside (82).

INSTITUTIONAL FACTORS To explain land-use changes, it is also important to understand institutions (political, legal, economic, and traditional) and their interactions with individual decision making (85, 108). Access to land, labor, capital, technology, and information is structured (and is frequently constrained) by local and national policies and institutions (109). Land managers have varying capabilities to participate in and to define these institutions. Relevant nonmarket institutions include: property-rights regimes; environmental policies; decision making systems on resource management (e.g., decentralization, democratization, and the role of the public, of civil society, and of local communities in decision making); information systems related to environmental indicators as they determine perception of changes in ecosystems; social networks representing specific interests related to resource management; conflict resolution systems concerning access to resources; and institutions that govern the distribution of resources and thus control economic differentiation.

There is often a mismatch between environmental signals reaching local populations and the macrolevel institutions (87, 110). Therefore, the rules used for making policies are important to ensure that local users are able to influence resource-management institutions (111). Institutions need to be considered at various scales, to identify the local mediating factors and adaptive strategies and to understand their interactions with national- and international-level institutions.

Many land-use changes are due to ill-defined policies and weak institutional enforcement, as exemplified by the widespread illegal logging in Indonesia linked to corruption and to the devolving of forest management responsibilities to the district level (112). On the other hand, recovery or restoration of land is also possible with appropriate land-use policies. Consolidation of landholdings and the shift from communal, traditional systems to formal, state-sanctioned regimes is a trend observed throughout the developing world (83). Examples of policies that influence land-use change are state policies to attain self-sufficiency in food (113); taxation, fiscal incentives, subsidies, and credits (93, 97, 114–116); price controls on agricultural inputs and outputs (87, 116); decentralization (113, 117); infrastructure support (87); (low) investments in monitoring and formally guarding natural resources (85); resource commodification (87, 116, 118, 119); land consolidation (120, 121), nationalization, and collectivization (87, 113); structural adjustment measures (101, 106, 122); and international environmental agreements.

With increasingly interconnected market forces and the rise of international environmental conventions, the impact of institutional drivers moves from the local to the global level. Land degradation is more prominent when macropolicies, either capitalist or socialist, undermine local adaptation strategies. In particular, perverse subsidies for road construction, agricultural production, forestry, and so forth are thought to be one of the biggest impediments to environmental sustainability (123).

CULTURAL FACTORS Numerous cultural factors also influence decision making on land use. Land managers have various motivations, collective memories, and personal histories. Their attitudes, values, beliefs, and individual perceptions influence land-use decisions—for instance through their perception of and attitude toward risk. Land-use decisions have intended and unintended consequences on ecosystems; these depend on the knowledge, information, and management skills available to land managers. Culture is often linked with political and economic inequalities, e.g., the status of women or ethnic minorities (76, 87), that affect resource access and land use. Understanding the controlling models of various actors may thus explain the management of resources, adaptive strategies, compliance or resistance to policies, or social learning and therefore social resilience in the face of land-use change.

GLOBALIZATION Researchers have recently argued that cross-cutting the local and national pathways of land-use/cover change are the many processes of globalization that amplify or attenuate the driving forces by removing regional barriers, weakening national connections, and increasing the interdependency among people and between nations. Globalization as such is not a driver of land-use change but is a process that underlies the other driving forces discussed above. Globalization accelerates or buffers the impact of these drivers on land use. For example, Barbier (124) identified land-use change as the immediate and principal environmental impact of economic liberalization and globalization—mostly trade liberalization and reforms to open up the agro-industrial sector—in Ghana and Mexico. Directly, increased agricultural productivity triggered forest conversion and increased land degradation from unsustainable production methods. Indirectly, agro-industrial development displaced the landless and rural poor, who were then pushed to marginal agricultural lands or to the forest frontier. Although the environmental effects of macroeconomic policies and trade liberalization are particularly important in countries with fragile ecosystems (e.g., semiarid lands and mangrove forests), international trade and other forms of globalization can also improve environmental conditions through green certification and eco labeling, wider and more rapid spread of technologies, better media coverage allowing international pressure on states that degrade their resources, and free circulation of people, which provides better educational and employment opportunities. Naylor et al. (125) showed, for example, that in a small island of Micronesia, international migration, foreign aid, and monetary remittances from family members living overseas have relieved the pressures of economic crowding on mangrove forests, despite an increase in population and a decline in local government jobs.

International institutions (including organizations within the U. N. system and nongovernmental organizations) can be instrumental in promoting and funding policies aimed at combating environmental degradation, setting political agendas, building consensus, and creating constraints and incentives for sustainable land management (126).

A Finite Set of Pathways of Land-Use Change

The various sectoral drivers of land-use change discussed above are strongly linked within and between levels of organization of human-environment systems. They interact directly, are linked via feedback, and thus often have synergetic effects. Any land manager also constantly makes trade-offs between different land-use opportunities and constraints associated with a variety of external factors. Moreover, various human-environment conditions react to and reshape the impacts of drivers differently, which leads to specific pathways of land-use change (82). The complexity in the combinations of causes giving rise to land-use change can be greatly reduced by recognizing that there are a limited number of ways in which these causes interact. In other words, a limited suite of processes and variables at any scale makes the problem tractable (127). The critical challenge is thus to identify dominant pathways and associated causes of land-use change. The risk factors associated with each pathway can then be identified.

Certain conditions appear repeatedly in case studies. They include but are not restricted to: loss of land productivity on sensitive areas following inappropriate use or the failure to maintain protective works (128, 129); development of the forest frontiers by weak state economies, for geopolitical reasons or to promote interest groups (94, 104); institutions in transition from communal to private land ownership in developing regions (93, 130); loss of entitlements to environmental resources (e.g., expropriation for large-scale agriculture, large dams, forestry projects, tourism, and wildlife conservation), that lead to an ecological marginalization of the poor (80, 131, 132); decrease in land availability due to encroachment by other land uses, such as land zoning for forest reserves, wilderness areas or agro-industrial plantations, which leads to the so-called tragedy of enclosure (96, 133); induced innovation and intensification (87, 134, 135), especially in peri-urban and market-accessible areas of developing regions (136); urbanization followed by changes in consumption patterns and in income distribution with differential rural impacts (87, 96, 120); new economic opportunities linked to new market outlets, changes in economic policies, or capital investments (114, 130, 137–139); breakdown of extended families with impacts on resource use efficiency (89, 90); inappropriate policy intervention giving rise to rapid modifications of landscapes and ecosystems (103, 140, 141); macroeconomic shocks and structural adjustment policies with undesirable consequences on natural resources (101, 106, 122, 142); lack of community's ability to cope with a deteriorating environmental situation, combined with absence of political will to mitigate damage and to alter the trajectory of change, which leads to delayed and ineffective social responses (10).

Case studies show that not all causes of land-use change and all levels of organization are equally important. For any given human-environment system, a limited number of causes are essential to predict the general trend in land use (127). This is the basis, for example, for the syndrome approach, which describes archetypical, dynamic, coevolutionary patterns of human-environment interactions (81). A taxonomy of syndromes links processes of degradation to both changes over time and status of state variables. The approach is applied at the intermediate functional scales that reflect processes taking place from the household level up to the international level. For example, the *overexploitation syndrome* represents the natural and social processes governing the extraction of biological resources through unsustainable industrial logging activities or other forms of resource use. Policy failure is one of the essential underlying driving forces of this syndrome (e.g., corruption, lobbyism, and weak or no law enforcement) (81). The typology of syndromes reflects expert opinion based on local case examples. The syndrome approach aims at a high level of generality in the description of mechanisms of environmental degradation.

Another approach, which has provided a classification of the situations in which environmental degradation occurs, is the study of regions at risk and environmental criticality by Kasperson et al. (10). Several case studies of regions under environmental degradation were described qualitatively by their histories. These qualitative trajectories were represented in terms of development of the wealth of the inhabitants and the state of the environment. A *critical environment* was defined as one in which the extent or the rate of environmental degradation precludes the maintenance of current resource-use systems or levels of human well-being, given feasible adaptations and the community's ability to mount a response (10). Different typical time courses of these variables were identified and interpreted with respect to more or less problematic future development of the regions. The Aral Sea, for example, was unquestionably a critical region after a few decades of Soviet-sponsored, ill-conceived large-scale irrigation schemes. Subsuming a particular case (e.g., the present situation and the history in a specified region) under one of these classes should allow for a restricted prognosis of its possible future development, which is a prerequisite for mitigation or adaptation.

Generic principles leading to environmental degradation can also emerge from careful comparison of diverse case studies. Kates & Haarmann (80) found a set of common interactive processes linking poverty and environmental degradation. Case studies told common tales of poor people's displacement from their lands, the division of their resources, and the degradation of their environments, which culminated in three major spirals of household impoverishment and environmental degradation driven by combinations of development and commercialization, population growth, poverty, and natural hazards. Lambin et al. (82) similarly identified typical pathways leading to tropical deforestation, agricultural intensification, rangeland modifications, and urbanization.

In summary, despite the large diversity of causes and situations leading to land-use change, there are some generalizable patterns of change that result from recurrent interactions between driving forces, following specific sequences of events. Even though, at the detailed level, these sequences may play out differently in specific situations, their identification may confer some predictive power by analogy with similar pathways in comparable regional and historical contexts.

A SYNTHESIS OF THE CAUSES OF LAND-USE CHANGE AND THEIR INTERACTIONS

The Five Fundamental High-Level Causes of Land-Use Change

Summarizing a large number of case studies, we find that land-use change is driven by a combination of the following fundamental high-level causes (Table 4):

TABLE 4 Typology of the causes of land-use change

	Resource scarcity causing pressure of production on resources	**Changing opportunities created by markets**	**Outside policy intervention**	**Loss of adaptive capacity and increased vulnerability**	**Changes in social organization, in resource access, and in attitudes**
Slow	Natural population growth and division of land parcels Domestic life cycles that lead to changes in labor availability Loss of land productivity on sensitive areas following excessive or inappropriate use Failure to restore or to maintain protective works of environmental resources Heavy surplus extraction away from the land manager	Increase in commercialization and agro-industrialization Improvement in accessibility through road construction Changes in market prices for inputs or outputs (e.g., erosion of prices of primary production, unfavorable global or urban-rural terms of trade) Off-farm wages and employment opportunities	Economic development programs Perverse subsidies, policy-induced price distortions and fiscal incentives Frontier development (e.g., for geopolitical reasons or to promote interest groups) Poor governance and corruption Insecurity in land tenure	Impoverishment (e.g., creeping household debts, no access to credit, lack of alternative income sources, and weak buffering capacity) Breakdown of informal social security networks Dependence on external resources or on assistance Social discrimination (ethnic minorities, women, members of lower classes or castes)	Changes in institutions governing access to resources by different land managers (e.g., shift from communal to private rights, tenure, holdings, and titles) Growth of urban aspirations Breakdown of extended family Growth of individualism and materialism Lack of public education and poor information flow on the environment
Fast	Spontaneous migration, forced population displacement, refugees Decrease in land availability due to encroachment by other land uses (e.g., natural reserves)	Capital investments Changes in national or global macro-economic and trade conditions that lead to changes in prices (e.g., surge in energy prices or global financial crisis) New technologies for intensification of resource use	Rapid policy changes (e.g., devaluation) Government instability War	Internal conflicts Illness (e.g., HIV) Risks associated with natural hazards (e.g., leading to a crop failure, loss of resource, or loss of productive capacity)	Loss of entitlements to environmental resources (e.g., expropriation for large-scale agriculture, large dams, forestry projects, tourism and wildlife conservation), which leads to an ecological marginalization of the poor

1. resource scarcity leading to an increase in the pressure of production on resources,
2. changing opportunities created by markets,
3. outside policy intervention,
4. loss of adaptive capacity and increased vulnerability, and
5. changes in social organization, in resource access, and in attitudes.

Some of these fundamental causes are experienced as constraints. They force local land managers into degradation, innovation, or displacement pathways. The other causes are associated with the seizure of new opportunities by land managers who seek to realize their diverse aspirations.

Each of these high-level causes can apply as slow evolutionary processes that change incrementally at the timescale of decades or more, or as fast changes that are abrupt and occur as perturbations that affect human-environment systems suddenly (Table 4). Only a combination of several causes, with synergetic interactions, is likely to drive a region into a critical trajectory (84).

Some of the fundamental causes leading to land-use change are mostly endogenous, such as resource scarcity, increased vulnerability and changes in social organization, even though they may be influenced by exogenous factors as well. The other high-level causes, such as changing market opportunities and policy intervention, are mostly exogenous, even though the response of land managers to these external forces is strongly mediated by local factors.

Mode of Interactions Between Causes of Change

The representation of interactions between these various causes of land-use change may be based on different patterns: one cause may completely dominate the other causes, assuming that land use in a given locality is influenced by whatever factor exerts the greatest constraint; factors driving land-use change can be connected as causal chains, i.e., interconnected in such a way that one or several variables (underlying causes, mainly) drive one or several other variables (proximate causes, mainly); different factors can intervene in concomitant occurrence, i.e., independent but synchronous operation of individual factors leading to land change; they may also intervene in synergetic factor combinations, i.e., several mutually interacting variables driving land-use change and producing an enhanced or increased effect due to reciprocal action and feedbacks between causes.

In meta-analyses of case studies of tropical deforestation (33) and dryland degradation or desertification by the same authors, the proportion of cases in which dominant, single, or key factors operate at either the proximate or underlying level was low (ca. 10% of the cases), as was the case with pure causal chains (ca. 5% to 8%). Concomitant occurrence of causes was more widespread (ca. 25%). The most common type of interaction was synergetic factor combinations (in 70% to 90% of the case studies reviewed).

In short,

$$\text{Land use} = f(\text{pressures, opportunities, policies, vulnerability, and social organization});$$

with

$$\text{pressures} = f(\text{population of resource users, labor availability, quantity of resources, and sensitivity of resources});$$
$$\text{opportunities} = f(\text{market prices, production costs, transportation costs, and technology});$$
$$\text{policies} = f(\text{subsidies, taxes, property rights, infrastructure, and governance});$$
$$\text{vulnerability} = f(\text{exposure to external perturbations, sensitivity, and coping capacity}); \text{ and}$$
$$\text{social organization} = f(\text{resource access, income distribution, household features, and urban-rural interactions})$$

with the functions f having forms that account for strong interactions between causes of land-use change.

Feedback and Endogeneity

In most cases, the patterns of causation discussed above are simplifications that are useful for communicating about particular environmental issues or for modeling. In reality, there are functional interdependencies between all the causes of land-use change, both at each organizational level, "horizontal interplay," and between levels of organization, "vertical interplay" (143).

Even at short timescales, the direction of causality may be difficult to establish, as illustrated by the case of roads and deforestation. For example, 81% of the deforestation in the Brazilian Amazon between 1991 and 1994 occurred within 50 kilometers of four major road networks (144). Is it the national demand for land and the high agricultural suitability of some forest areas that lead to policy decisions to expand the road network in these areas, which then gives access to the forest for migrants who clear land? Or is it the expansion of local logging or agricultural activities in some forest areas that then justifies the construction of new roads to link these active production areas to existing markets? Or does the construction of a road for reasons unrelated to land use in the forest (e.g., to connect major cities) induce new deforestation by its mere presence, through a spatial redistribution of population and activities? Or, in the latter case, does the road simply attract to a given location a preexisting demand for land that would have led to deforestation elsewhere if the road had not been built? In other words, is a road an endogenous or exogenous factor in deforestation and does it affect just the location or also the quantity of deforestation in a given country? The likely answer to these questions is that, in most cases, national demand for land, policies to develop the forest frontier, capital investments in logging and agricultural activities, population movements, commodification of the economy, the development of urban markets, and infrastructure expansion are highly interdependent and coevolve in close interaction as part of a general transformation of society and of its interaction with its natural environment.

As the timescale of analysis expands, all causes of land-use change—from demographic changes to technological innovations, which include new environmental policies—become endogenous to the human-environment system and are affected in some degree by land-use change. Actually, the changes in ecosystem goods and services that result from land-use change lead to important feedback on the drivers of land-use change. Changes in ecosystems affect the availability and quality of some of the natural resources that are essential to sustain livelihood, create opportunities and constraints for new land uses, induce institutional changes at the local to global levels in response to perceived and anticipated resource degradation, modify the adaptive capacity of land managers (by affecting their health, for example), and give rise to social changes in the form of income differentiation (when there are winners and losers in environmental change) or increased social complexity (e.g., by increasing interactions between urban and rural systems).

Land-Use Change as an Emergent Property of Complex Adaptive Systems

Land use is never static, but it is constantly changing in response to dynamic interaction between drivers and feedback from land-use change to these drivers. In other words, human-environmental systems are complex adaptive systems in which properties, such as land use, emerge from the interactions among the various components of the entire system, which themselves feed back to influence the subsequent development of those interactions (127). Land-use change is a spatial property observed at the scale of a landscape. It is the sum of many small, local-scale changes in land allocation that reinforce or cancel each other. These changes are the product of multiple decisions resulting from interactions between diverse agents, who act under certain conditions, anticipate future outcomes of their decisions, and adapt their behaviors to changes in external (e.g., the market) and internal (e.g., their aspirations) conditions. In most cases, these decisions are made without central direction, unless there are central planning systems. Land-use change is thus a complex large-scale spatial behavior that emerges from the aggregate interactions of less complex agents. Human-environment systems associated with land use have similar attributes and are governed by mechanisms and processes similar to those of other complex adaptive social or biological systems (145–147).

The exact future of the behavior of coupled human-environment systems is often unpredictable because it is emergent rather than predetermined. Hence, there is an interest in place-based research as a method to reveal a large repertoire of pathways of land-use change, in a range of human-environment conditions.

Land-Use Transitions

Land-use change is associated with other societal and biophysical changes through a series of transitions (148). A transition can be defined as a process of societal change in which the structural character of society (or a complex subsystem of society) transforms (149). It results from a set of connected changes, which reinforce each other but take place in several different components of the system. Multiple causality and coevolution of different sectors of society caused by interacting developments are central to the concept of transition. Transitions in land use must be viewed as multiple and reversible dynamics. A transition is not a fixed pattern, nor is it deterministic. It is not set in advance, and there is large variability in specific trajectories. There is thus a strong notion of instability and indeterminacy in land-use transitions. Transitions should be viewed as "possible development paths where the direction, size, and speed can be influenced through policy and specific circumstances" (149).

The concept of transition has been applied in land-use change studies at different spatial and temporal scales. A forest transition has been described at a national scale to represent the change from decreasing to expanding national forest areas that has taken place over a century or more in several European countries and in North America, by afforestation and natural regeneration mostly on abandoned marginal agricultural land once societies began to industrialize and urbanize (150, 151). Forests in the Mediterranean basin did not make this transition. Some regions in the tropics currently show signs of significant reforestation. A predominantly national focus in forest transition studies (150–152) has been increasingly complemented by analyses at the subnational scale (153, 154). Case studies have also identified transition-like trajectories that suggest, over a decade or so, households undertake management of already cleared areas following a period of rapid deforestation, stop deforesting, and even undertake afforestation within their individual parcels (155–157).

INTEGRATIVE FRAMEWORKS TO UNDERSTAND LAND-USE/COVER CHANGES

How to overcome the somewhat futile observation that everything is interrelated? The level of integration in research on land-use/land-cover change requires a combination of perspectives of understanding: the agent-based, the systems, and the narrative approaches (19). Each perspective approaches the impact on land of the interactions between macrostructure and microagency from a different vantage point. These perspectives can be and are combined in various ways in integrated, place-based research on causes and impacts of land-use change; examples include the Yucatán (158), the Serengeti-Mara ecosystem (132), the Nang Rong District in northeastern Thailand (159, 160), the Ecuadorian Amazon (161), the Belgian Ardennes (162), the Yaqui valley in Mexico (163), the African Sahel

(164, 165), and other integrated land change studies over a particular geographical region. These perspectives still have to be integrated in the modeling of land-use change.

Agent-Based Perspective

The agent-based perspective is centered on the general nature and rules of land-use decision making by individuals. It represents the motivations behind decisions and the external factors that influence decisions about land use. It applies approaches that range from the rational decision making of neoclassical economics to household, gender, class, and other dimensions common to the social and behavioral sciences. Local ecosystem managers have many motives, some intentional and others unconscious, related to economic, traditional, emotional or biophysical factors (76). Economic models of land-use change, for example, assume that land managers attempt to fulfill their needs and meet their expectations by accommodating economic, social, and environmental constraints (utility optimization). Land managers evaluate expected outcomes of their land-use decisions. If undesired environmental impacts are foreseen, they modify factor allocation (22).

As an example of the agent-based perspective, authors have analyzed the diversity of responses by land managers to population growth. Whereas the emphasis of Boserup's work (166) is on technological responses, Bilsborrow (167) analyzed several demographic responses in the face of land shortage and declining yields. They are of two sorts: outmigration and fertility reduction through postponement of marriage or reduction in marital fertility. Bilsborrow & Ogendo (168) further describe local changes in tenure arrangements, which can be the first adaptations of land-use practices to population growth. They usually follow the sequence of distribution of idle land for agricultural use, reduction of landholding size in the community, creation of new categories of access rights, and reclassification of old ones to exclude nonpermanent members. Moreover, these tenurial, technological, and demographic responses can be multiphasic, i.e., occurring simultaneously—as conceptualized by Davis (169), rather than sequential. Their effects are thus difficult to separate.

Microeconomic approaches to land-use changes explain spatial configurations of changes. Any parcel of land, given its attributes and location, is assumed to be allocated to the use that earns the highest rent (170). This rent is a function of the returns and costs of land conversion, given supply and demand functions of the land market, which is assumed to be competitive (171). Deforestation, for example, is driven by choices by land managers among alternative rents (172, 173). Microeconomic approaches usually assume that the agents have the ability to make informed predictions and plans and that they are risk minimizers. After exploring all options available to them, individuals make rational decisions based on available information, obligations, and expectations (social as well as economic) to balance anticipated returns and risks.

Systems Perspective

The systems/structures perspective explains land-use change through the organization and institutions of society (174). Institutions, such as governments, communities, or markets, operate interactively at different spatial and temporal scales; the institutions link local conditions to global processes and vice versa. Although some institutions are direct drivers of change, others, such as markets, are intricately linked to individual decisions. The systems perspective represents the dynamics of economy-environment linkages operating at regional to global scales. It has to cope with issues that include technological innovations, policy and institutional changes, collective ownership of land resources, rural-urban dynamics, and macroeconomic transformations.

The systems perspective highlights, for example, how communities are trapped in a degradational pathway given complex mechanisms that may have their roots outside the area subjected to degradation. For instance, Blaikie & Brookfield (175), Leonard (131) and Kates & Haarman (80) discuss the process of marginalization of poor people in remote and ecologically fragile rural areas. This ecological marginalization usually follows population growth, agricultural modernization—associated with mechanization and land consolidation—inequalities in land tenure in the most fertile and accessible agricultural regions, or other pressures of social or political origin. It leads to migration of poor farmers into areas with a high ecological sensitivity for which existing management practices may be inadequate.

Narrative Perspective

The narrative perspective seeks depth of understanding through historical detail and interpretation (176, 177). It tells a land-use/cover change story for a specific locality (178–180). Historical analyses of landscape grasp all the complexity of events, in particular stochastic or nonrandom but unpredictable events that significantly affect land-use/land-cover changes. It includes changing political economies, environmental feedback on land use, and external shocks (181). The narrative perspective recognizes the path dependence of recent evolutions. It avoids the simplifications and erroneous interpretations that could result from studies focused only on the present and immediate past, outside the context of longer histories of human-environment interactions (109). For example, Fairhead & Leach's (182) historical study of contemporary forest islands in Guinea showed that these were human creations in a savanna landscape, where farmers have turned fallow vegetation more woody around their villages. These patches of dense forests in the savanna had long been regarded as the last relics of a once more extensive forest cover, degraded due to its inhabitants' land use. The narrative approach also allows distilling from changing human-environment conditions those dynamics crosscutting different eras or episodes of use and occupation and those unique to individual episodes (181).

Scenarios generated to project future land-use changes or to identify land-use patterns with certain optimality characteristics are based on narrative story lines to describe consistently the relationships between driving forces of environmental changes and their evolution (183). The scenarios are hypothetical sequences of events that provide alternative images of how the future might unfold. Scenarios consist of states, driving forces, events, consequences, and actions that are internally consistent and plausible (183). They provide insights into the present by drawing analogies between historical and current situations.

CONCLUSION AND FUTURE RESEARCH

Significant progress in the quantification and understanding of land-use/cover changes has been achieved over the last decade. Much remains to be learned, however, before we can fully assess and project the future role of land-use/cover change in the functioning of the earth system and identify conditions for sustainable land use. New estimates of areas and rates of major land-use/cover conversions have greatly narrowed down uncertainties. Sometimes initial estimates of the spatial importance of these changes have been revised downward. But often, the significance of land-use/cover change for earth system processes has been revised upward. A number of more subtle land changes still need to be better quantified at a global scale. This is particularly the case for anthropogenic changes that strongly interact with natural environmental variability and therefore require longitudinal data over a long time period for a reliable assessment.

Analyses of the causes of land-use change have moved from simplistic single-cause explanations to an understanding that integrates multiple causes and their complex interactions. A few general pathways leading to land-use change have been identified from a wealth of local case studies. This inductive process of generalization paves the way for the development of more realistic models of land-use change. Nevertheless, different perspectives of understanding still tend to follow different lines of explanation of the causes of land-use change because each focuses on specific organizational levels and temporal scales of the human-environment systems. Whereas a systems perspective tends to focus on gradual and progressive processes of change at the scale of large entities, the agent-based perspective deals with people's own foreseeable futures at the individual level, and the narrative perspective adopts a much longer time horizon and focuses on critical events and abrupt transitions. Different assumptions about temporality lead to varying explanations and interpretations of the causes and significance of environmental changes. These assumptions should be made explicit to facilitate the development of an integrative theory of human-environment relationships. We also argued in this paper that a systematic analysis of local scale land-use change studies, conducted over a range of timescales, helps to uncover general principles to provide an explanation and prediction of new land-use changes.

Improved understanding of the complex dynamic processes underlying land-use change will allow more reliable projections and more realistic scenarios of future changes. Crucial to projections is understanding factors that control positive and negative feedback in land-use change. Positive feedback loops amplify change and lead, in some cases, to a rapid degradation of ecosystems and the impoverishment of the societies using these ecosystems. By contrast, institutional and technological innovations may lead to negative feedback loops that decrease the rate of change or even reverse land-use/cover change trends. The relative strength of amplifying and attenuating feedback can be influenced by policies that control switches between land-use/cover change regimes dominated by positive or negative feedback. The analysis of interaction, coherence, or conflict between social and biophysical responses to changes in both ecosystem services and earth system processes caused by land changes is still a largely unresearched area. It will be a central focus of the new Land project of the IGBP and IHDP.

Improved understanding of processes of land-use change has led to a shift from a view condemning human impact on the environment as leading mostly to a deterioration of earth system processes to emphasis on the potential for ecological restoration through land management (184). This change reflects an evolution of the research questions, methods, and scientific paradigm.

First, initial concerns about global land-use/cover change arose from the realization that land transformation influences climate change and reduces biotic diversity, hence the interest in deforestation, desertification, and other changes in natural vegetation. The more recent focus on issues related to ecosystem goods and services, sustainability, and vulnerability has led to a greater emphasis on the dynamic coupling between human societies and their ecosystems at a local scale.

Second, research methods applied in land-use/cover change research were initially largely influenced by advances in remote sensing. This technology has led to an emphasis on short timescales, because earth observation data have been available only for a few decades. Recently, a wide range of other methods have been used to reconstruct long-term changes in landscapes. This change in temporal frame has led to a greater consideration of the long-term processes of ecological restoration and land-use transition.

Finally, whereas the notion of equilibrium used to dominate thinking about environmental change, a nonequilibrium paradigm, as well as concepts related to complex system dynamics, is now influencing land-use/cover change research. Rather than interpreting deviations from a predisturbance state as problematic, land-use changes are now increasingly analyzed as part of the system interactions leading to coevolution of natural and social systems. Throughout their history, human societies have coevolved with their environment through change, instability, and mutual adaptation. The coupled human-environment systems should therefore be considered as a whole when we assess sustainability and vulnerability.

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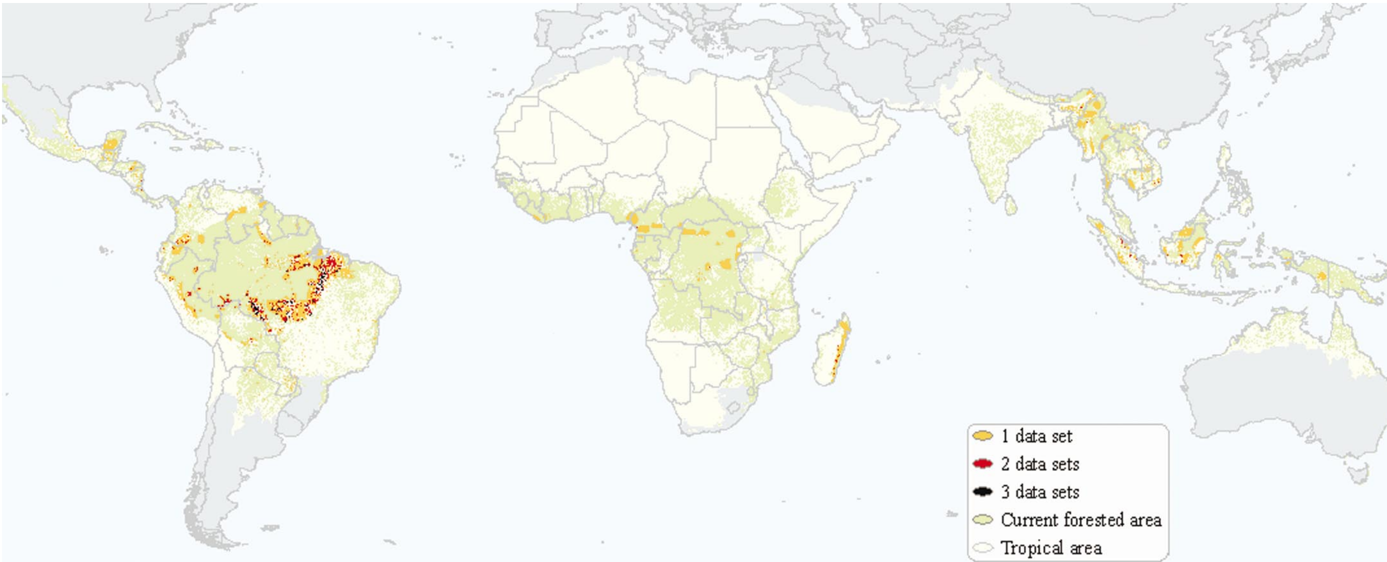

Figure 1 Main tropical deforestation fronts in the 1980s and 1990s. The map is based on three data sets: (a) the deforestation hotspots in the humid tropics of the Tropical Ecosystem Environment Observation by Satellite (TREES) project (34), (b) a time series analysis of tree cover based on 8-km resolution data from the National Oceanic and Atmospheric Administration's advanced very high resolution radiometer (AVHRR) (31), and (c) the Amazon Basin deforestation maps derived from time series of Landsat Thematic Mapper (Landsat TM) data (35). These maps were overlaid and combined to identify areas where high rates of deforestation were measured by several of the datasets. *Green* areas are intact forests. The map indicates the number of times each 0.1° grid was identified as being affected by rapid deforestation by the different datasets (*orange*, pixels detected as hotspot by one dataset, *red*, pixels detected as hotspot by two datasets, *black*, pixels detected as hotspot by three datasets) (36).

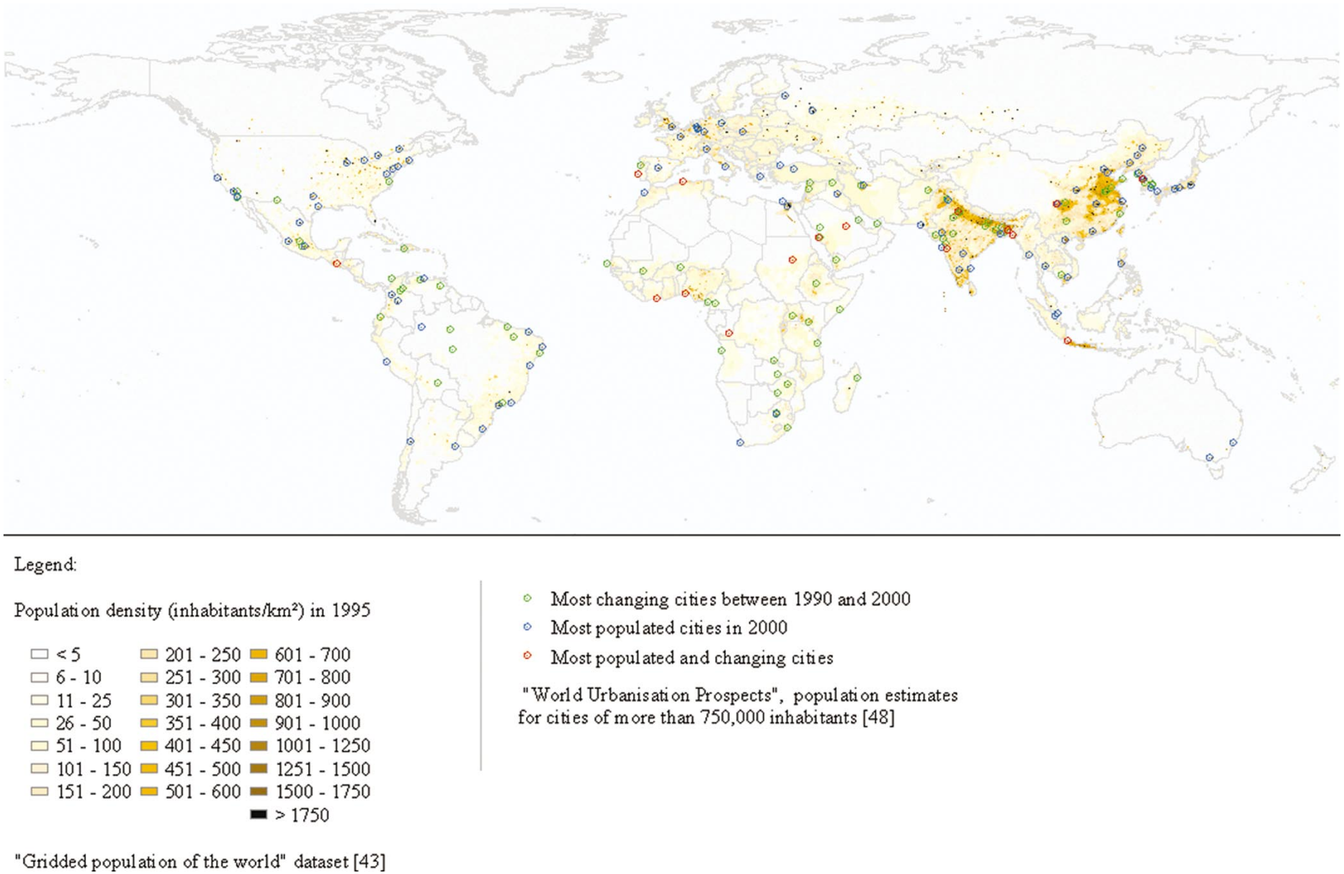

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Figure 2 Population density in 1995 and most populated and changing cities from 1990 to 2000. The map is based on the 2001 revision of the "World Urbanization Prospects" (43), which provides population estimates in cities of more than 750,000 inhabitants for the years 1990 and 2000, and the "gridded population of the world" (48), which provides population estimates in 1995. The first dataset focuses on megacities whereas the second includes less populated areas. *Green circles* represent the most changing cities between 1990 and 2000, *blue circles* the most populated cities in 2000, and *red circles* the most changing and populated cities. The background color scale represents the population densities in 1995 (from less than five inhabitants in *gray* to more than 1750 inhabitants/km^2 in *dark orange*) (36).

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ERRATA

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