Global Consequences of Land Use

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Land use has generally been considered a local environmental issue, but it is becoming a force of global importance. Worldwide changes to forests, farmlands, waterways, and air are being driven by the need to provide food, fiber, water, and shelter to more than six billion people. Global croplands, pastures, plantations, and urban areas have expanded in recent decades, accompanied by large increases in energy, water, and fertilizer consumption, along with considerable losses of biodiversity. Such changes in land use have enabled humans to appropriate an increasing share of the planet's resources, but they also potentially undermine the capacity of ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality, and ameliorate infectious diseases. We face the challenge of managing trade-offs between immediate human needs and maintaining the capacity of the biosphere to provide goods and services in the long term.

Land-use activities—whether converting natural landscapes for human use or changing management practices on human-dominated lands—have transformed a large proportion of the planet's land surface. By clearing tropical forests, practicing subsistence agriculture, intensifying farmland production, or expanding urban centers, human actions are changing the world's landscapes in pervasive ways (*1*, *2*) (Fig. 1, fig. S1, and table S1). Although land-use practices vary greatly across the world, their ultimate outcome is generally the same: the acquisition of natural resources for immediate human needs, often at the expense of degrading environmental conditions.

Several decades of research have revealed the environmental impacts of land use throughout the globe, ranging from changes in atmospheric composition to the extensive modification of Earth's ecosystems (*3*–*6*). For example, land-use practices have played a role in changing the global carbon cycle and, possibly, the global climate: Since 1850, roughly 35% of anthropogenic CO_2 emissions resulted directly from land use (*7*). Land-cover changes also affect regional climates through changes in surface energy and water balance (*8*, *9*). Humans have also transformed the hydrologic cycle to provide freshwater for irrigation, industry, and domestic consumption (*10*, *11*). Furthermore, anthropogenic nutrient inputs to the biosphere from fertilizers and atmospheric pollutants now exceed natural sources and have widespread effects on water quality and coastal and freshwater ecosystems (*4*, *12*). Land use has also caused declines in biodiversity through the loss, modification, and fragmentation of habitats; degradation of soil and water; and overexploitation of native species (*13*) (SOM Text S1).

Ironically, just as our collective land-use practices are degrading ecological conditions across the globe, humanity has become dependent on an ever-increasing share of the biosphere's resources. Human activities now appropriate nearly one-third to one-half of global ecosystem production (*14*), and as development and population pressures continue to mount, so could the pressures on the biosphere. As a result, the scientific community is increasingly concerned about the condition of global ecosystems and "ecosystem services" (*15*, *16*) (SOM Text S2).

Land use thus presents us with a dilemma. On one hand, many land-use practices are absolutely essential for humanity, because they provide critical natural resources and ecosystem services, such as food, fiber, shelter, and freshwater. On the other hand, some forms of land use are degrading the ecosystems and services upon which we depend, so a natural question arises: Are land-use activities degrading the global environment in ways that may ultimately undermine ecosystem services, human welfare, and the long-term sustainability of human societies? Here, we examine this question and focus on a subset of global ecosystem conditions we consider most affected by land use. We also consider the challenge of reducing the negative environmental impacts of land use while maintaining economic and social benefits.

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Food Production

Together, croplands and pastures have become one of the largest terrestrial biomes on the planet, rivaling forest cover in extent and occupying ~40% of the land surface (*17*, *18*) (Fig. 2). Changing land-use practices have enabled world grain harvests to double in the past four decades, so they now exceed ~2 billion tons per year (*19*). Some of this increase can be attributed to a ~12% increase in world cropland area, but most of these production gains resulted from "Green Revolution" technologies, including high-yielding cultivars, chemical fertilizers and pesticides, and mechanization and irrigation (*4*, *20*) (fig. S2A). During the past 40 years, there has been a ~700% increase in global fertilizer use (*4*, *5*) and a ~70% increase in irrigated cropland area (*21*, *22*).

Although modern agriculture has been successful in increasing food production, it has also caused extensive environmental damage. For example, increasing fertilizer use has led to the degradation of water quality in many regions (*4*, *12*, *13*) (fig. S2B). In addition, some irrigated lands have become heavily salinized, causing the worldwide loss of ~1.5 million hectares of arable land per year, along with an estimated $11 billion in lost production (*20*). Up to ~40% of global croplands may also be experiencing some degree of soil erosion, reduced fertility, or overgrazing (*20*). The loss of native habitats also affects agricultural production by degrading the services of pollinators, especially bees (*23*, *24*). In short, modern agricultural land-use practices may be trading short-term increases in food production for long-term losses in ecosystem services, including many that are important to agriculture.

Freshwater Resources

Land use can disrupt the surface water balance and the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow. Surface runoff and river discharge generally increase when natural vegetation (especially forest) is cleared (*25*, *26*). For instance, the Tocantins River basin in Brazil showed a ~25% increase in river discharge between 1960 and 1995, coincident with expanding agriculture but no major change in precipitation (*26*).

Water demands associated with land-use practices, especially irrigation, directly affect freshwater supplies through water withdrawals and diversions. Global water withdrawals now total ~3900 $km^3 yr^{-1}$, or ~10% of the total global renewable resource, and the consumptive use of water (not returned to the watershed) is estimated to be ~1800 to 2300 $km^3 yr^{-1}$ (*22*, *27*) (fig. S3A). Agriculture alone accounts for ~85% of global consumptive use (*22*). As a result, many large rivers, especially in semiarid regions, have greatly reduced flows, and some routinely dry up (*21*, *28*). In addition, the extraction of groundwater reserves is almost universally unsustainable and has resulted in declining water tables in many regions (*21*, *28*) (fig. S2, B and C).

Water quality is often degraded by land use. Intensive agriculture increases erosion and sediment load, and leaches nutrients and agricultural chemicals to groundwater, streams, and rivers. In fact, agriculture has become the largest source of excess nitrogen and phosphorus to waterways and coastal zones (*12*, *29*). Urbanization also substantially degrades water quality, especially where wastewater treatment is absent. The resulting degradation of inland and coastal waters impairs water supplies, causes oxygen depletion and fish kills, increases blooms of cyanobacteria (including toxic varieties), and contributes to waterborne disease (*12*, *30*).

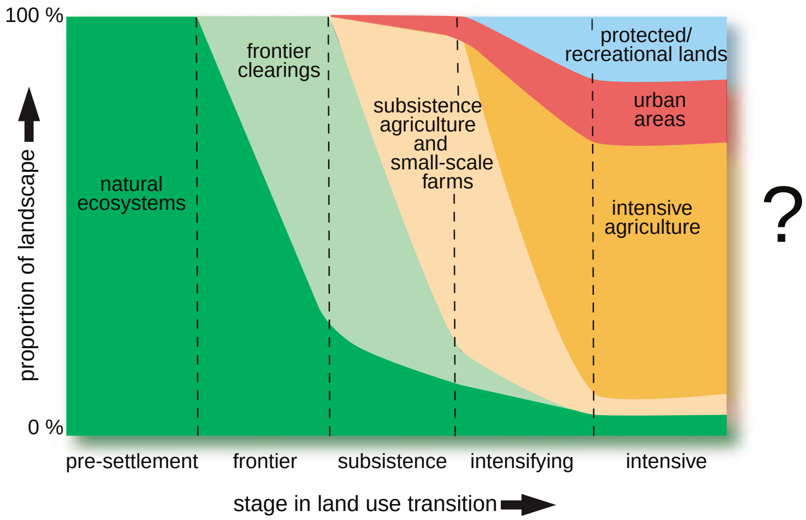

Fig. 1. Land-use transitions. Transitions in land-use activities that may be experienced within a given region over time. As with demographic and economic transitions, societies appear also to follow a sequence of different land-use regimes: from presettlement natural vegetation to frontier clearing, then to subsistence agriculture and small-scale farms, and finally to intensive agriculture, urban areas, and protected recreational lands. Different parts of the world are in different transition stages, depending on their history, social and economic conditions, and ecological context. Furthermore, not all parts of the world move linearly through these transitions. Rather, some places remain in one stage for a long period of time, while others move rapidly between stages. [Adapted from (*1*) and (*2*)]

Forest Resources

Land-use activities, primarily for agricultural expansion and timber extraction, have caused a net loss of ~7 to 11 million km^2 of forest in the past 300 years (*17*, *32*, *33*). Highly managed forests, such as timber plantations in North America and oil-palm plantations in Southeast Asia, have also replaced many natural forests and now cover 1.9 million km^2 worldwide (*31*).

Many land-use practices (e.g., fuel-wood collection, forest grazing, and road expansion) can degrade forest ecosystem conditions—in terms of productivity, biomass, stand structure, and species composition—even without changing forest area. Land use can also degrade forest conditions indirectly by introducing pests and pathogens, changing fire-fuel loads, changing patterns and frequency of ignition sources, and changing local meteorological conditions (*34*).

In many parts of the world, especially in East Asian countries, reforestation and afforestation are increasing the area of forested lands (*35*). Furthermore, forest management in many regions is acting to improve forest conditions. For example, inadvertent nitrogen fertilization, peatland drainage, and direct management efforts increased the standing biomass of European forests by ~40% between 1950 and 1990, while their area remained largely unchanged (*36*, *37*). These forests have become a substantial sink of atmospheric carbon (~0.14 Pg C yr^{-1} in the 1990s) (*37*), although other ecosystem services (including those provided by peatlands) and biodiversity are likely diminished.

Regional Climate and Air Quality

Land conversion can alter regional climates through its effects on net radiation, the division of energy into sensible and latent heat, and the partitioning of precipitation into soil water, evapotranspiration, and runoff. Modeling studies demonstrate that land-cover changes in the tropics affect climate largely through water-balance changes, but changes in temperate and boreal vegetation influence climate primarily through changes in the surface radiation balance (*38*). Large-scale clearing of tropical forests may create a warmer, drier climate (*39*), whereas clearing temperate and boreal forest is generally thought to cool the climate, primarily through increased albedo (*40*) (table S2, A and B).

Urban ''heat islands'' are an extreme case of how land use modifies regional climate. The reduced vegetation cover, impervious surface area, and morphology of buildings in cityscapes combine to lower evaporative cooling, store heat, and warm the surface air (*41*). A recent analysis of climate records in the United States suggests that a major portion of the temperature increase during the last several decades resulted from urbanization and other land-use changes (*9*). Land-cover change has also been implicated in changing the regional climate in China; recent analyses suggest that the daily diurnal temperature range has decreased as a result of urbanization (*42*).

Land-use practices also change air quality by altering emissions and changing the atmospheric conditions that affect reaction rates, transport, and deposition. For example, tropospheric ozone (O_3) is particularly sensitive to changes in vegetation cover and biogenic emissions. Land-use practices often determine dust sources, biomass burning, vehicle emission patterns, and other air pollution sources. Furthermore, the effects of land use on local meteorological conditions, primarily in urban heat islands, also affect air quality: Higher urban temperatures generally cause O_3 to increase (*43*).

Infectious Disease

Habitat modification, road and dam construction, irrigation, increased proximity of people and livestock, and the concentration or expansion of urban environments all modify the transmission of infectious disease and can lead to outbreaks and emergence episodes (*44*). For example, increasing tropical deforestation coincides with an upsurge of malaria and/or its vectors in Africa, Asia, and Latin America, even after accounting for the effects of changing population density (*44*, *45*).

Disturbing wildlife habitat is also of particular concern, because ~75% of human diseases have links to wildlife or domestic animals (*44*). Land use has been associated with the emergence of bat-borne Nipah virus in Malaysia (*46*), cryptosporidiosis in Europe and North America, and a range of foodborne illnesses globally (*47*). In addition, road building is linked to increased bushmeat hunting, which may have played a key role in the emergence of human immunodeficiency virus types 1 and 2; simian foamy virus was recently documented in hunters, confirming this mechanism of cross-species transfer (*48*).

The combined effects of land use and extreme climatic events can also have serious impacts, both on direct health outcomes (e.g., heat mortality, injury, fatalities) and on ecologically mediated diseases. For example, Hurricane Mitch, which hit Central America in 1998, exhibited these combined effects: 9,600 people perished, widespread water- and vector-borne diseases ensued, and one million people were left homeless (*49*). Areas with extensive deforestation and settlements on degraded hillsides or floodplains suffered the greatest morbidity and mortality (*50*).

Confronting the Effects of Land Use

Current trends in land use allow humans to appropriate an ever-larger fraction of the biosphere's goods and services while simultaneously diminishing the capacity of global ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality, and mediate infectious diseases. This assertion is supported across a broad range of environmental conditions worldwide, although some (e.g., alpine and marine areas) were not considered here. Nevertheless, the conclusion is clear: Modern land-use practices, while increasing the short-term supplies of material goods, may undermine many ecosystem services in the long run, even on regional and global scales.

Confronting the global environmental challenges of land use will require assessing and managing inherent trade-offs between meeting immediate human needs and maintaining the capacity of ecosystems to provide goods and services in the future (Fig. 3) (*2*, *16*). Assessments of trade-offs must recognize that land use provides crucial social and economic benefits, even while leading to possible long-term declines in human welfare through altered ecosystem functioning (*2*).

Sustainable land-use policies must also assess and enhance the resilience of different land-use practices. Managed ecosystems, and the services they provide, are often vulnerable to diseases, climatic extremes, invasive species, toxic releases, and the like (*51*–*53*). Increasing the resilience of managed landscapes requires practices that are more robust to disturbance and can recover from unanticipated "surprises."

There is an increasing need for decision-making and policy actions across multiple geographic scales and multiple ecological dimensions. The very nature of the issue requires it: Land use occurs in local places, with real-world social and economic benefits, while potentially causing ecological degradation across local, regional, and global scales. Society faces the challenge of developing strategies that reduce the negative environmental impacts of land use across multiple services and scales while maintaining social and economic benefits.

What strategies can ameliorate the detrimental effects of land use? Examples of land-management strategies with environmental, social, and economic benefits include increasing agricultural production per unit land area, per unit fertilizer input, and per unit water consumed (*19*, *21*, *54*, *55*); maintaining and increasing soil organic matter in croplands, which is a key to water-holding capacity, nutrient availability, and carbon sequestration

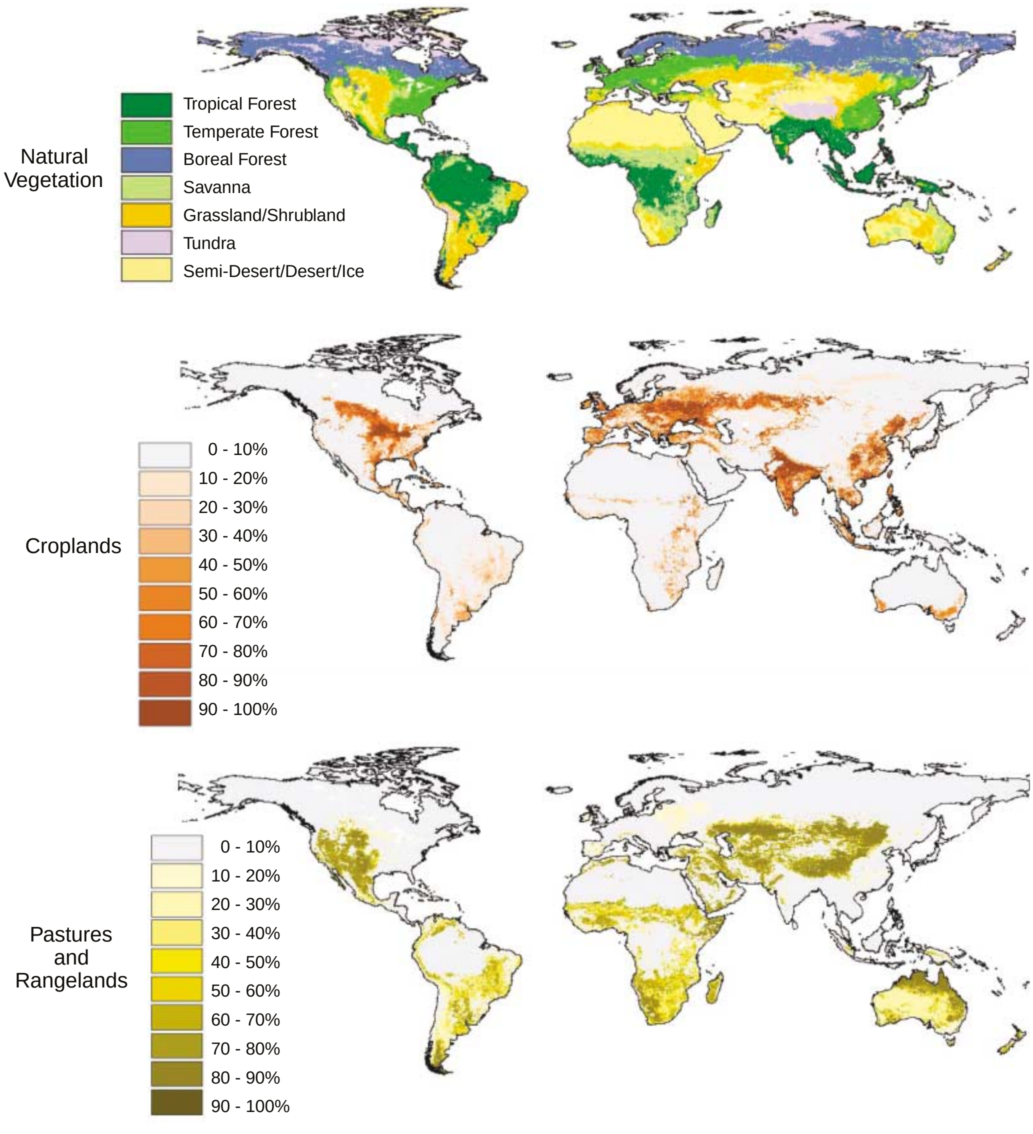

Fig. 2. Worldwide extent of human land-use and land-cover change. These maps illustrate the geographic distribution of "potential vegetation" (top), vegetation that would most likely exist in the absence of human land use, and the extent of agricultural land cover (including croplands and pastures) (middle and bottom) across the world during the 1990s. [Adapted from (*17*) and (*18*)]

(*56–58*); increasing green space in urban areas, thereby reducing runoff and "heat island" effects; employing agroforestry practices that provide food and fiber yet maintain habitats for threatened species; and maintaining local biodiversity and associated ecosystem services such as pollination and pest control. Many of these strategies involve management of landscape structure through the strategic placement of managed and natural ecosystems, so the services of natural ecosystems (e.g., pest control by natural predators, pollination by wild bees, reduced erosion with hedgerows, or filtration of runoff by buffer strips) are available across the landscape mosaic.

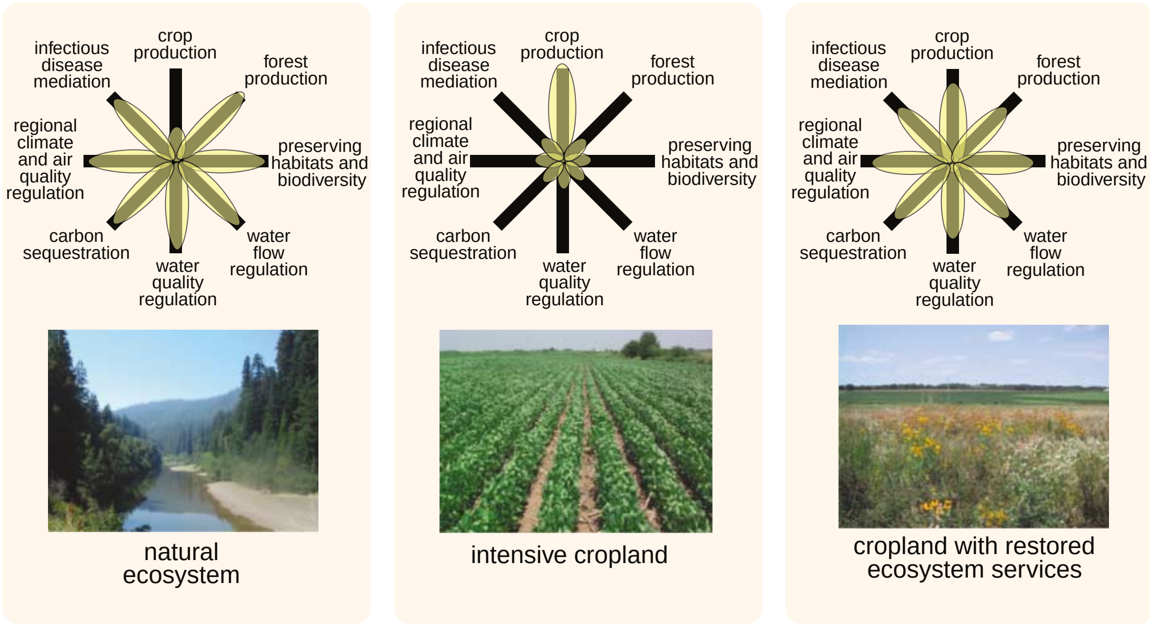

Fig. 3. Conceptual framework for comparing land use and trade-offs of ecosystem services. The provisioning of multiple ecosystem services under different land-use regimes can be illustrated with these simple "flower" diagrams, in which the condition of each ecosystem service is indicated along each axis. (In this qualitative illustration, the axes are not labeled or normalized with common units.) For purposes of illustration, we compare three hypothetical landscapes: a natural ecosystem (left), an intensively managed cropland (middle), and a cropland with restored ecosystem services (right). The natural ecosystems are able to support many ecosystem services at high levels, but not food production. The intensively managed cropland, however, is able to produce food in abundance (at least in the short run), at the cost of diminishing other ecosystem services. However, a middle ground—a cropland that is explicitly managed to maintain other ecosystem services—may be able to support a broader portfolio of ecosystem services.

Local-scale case studies, drawn from a set of worldwide examples, illustrate how land-use practices can offer "win-win-win" environmental, social, and economic benefits:

(i) New York City purchased development rights in watersheds of the Catskill Mountains, which provide water purification services, for ~US$1 billion, instead of building a filtration plant for ~US$6 billion to $8 billion plus annual operating costs of ~US$300 million (*59*).

(ii) Forests in the Yangtze watershed help moderate the discharge of river water, decreasing wet-season flow and enhancing dry-season flow. As a result, the Gezhouba hydroelectric plant produces an additional 40 million kilowatt-hours per year, worth ~US$610,000 per year, or the equivalent of ~40% of the forestry income from the region (*60*).

(iii) Coffee farms within ~1 km of forest benefit from wild pollinators, which can increase coffee yields by ~20% and reduce the frequency of small misshapen coffee beans by ~27% (*24*).

(iv) *Parus major*, a cavity-nesting bird of Europe, reduces the abundance of harmful caterpillars in apple orchards by as much as 50 to 99%. In the Netherlands, the foraging of *P. major* increased apple yields by ~4.7 to 7.8 kg per tree (*61*).

(v) Reflective roofing, green space, and increased shade reduce the effect of urban heat islands, with associated reductions in smog, heat-related mortality, and electricity demands from air conditioning. With such measures, a city like Sacramento, California, could lower its energy costs by ~US$26 million per year and reduce peak ozone concentrations by ~6.5% (*62*).

(vi) Integrated pest management for malaria control (e.g., using larvivorous fish) can reduce the need for chemical pesticides while increasing food supplies. In China, for example, stocking rice paddies with edible fish reduced malaria cases and simultaneously enhanced protein nutrition (*63*).

Developing and implementing regional land-use strategies that recognize both short- and long-term needs, balance a full portfolio of ecosystem services, and increase the resilience of managed landscapes will require much more cross-disciplinary research on human-dominated ecosystems (*16*). However, it will also benefit from closer collaboration between scientists and practitioners—linking, for example, ecologists and land-use planners, hydrologists and farmers, climatologists and architects, and entomologists and physicians. A wide array of skills will be needed to better manage our planet's landscapes and balance human needs, the integrity of ecological infrastructure, the continued flow of ecosystem services, and the long-term health of people and the biosphere.

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