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Global land use change, economic globalization, and the looming land scarcity

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A central challenge for sustainability is how to preserve forest ecosystems and the services that they provide us while enhancing food production. This challenge for developing countries confronts the force of economic globalization, which seeks cropland that is shrinking in availability and triggers deforestation. Four mechanisms—the displacement, rebound, cascade, and remittance effects—that are amplified by economic globalization accelerate land conversion. A few developing countries have managed a land use transition over the recent decades that simultaneously increased their forest cover and agricultural production. These countries have relied on various mixes of agricultural intensification, land use zoning, forest protection, increased reliance on imported food and wood products, the creation of off-farm jobs, foreign capital investments, and remittances. Sound policies and innovations can therefore reconcile forest preservation with food production. Globalization can be harnessed to increase land use efficiency rather than leading to uncontrolled land use expansion. To do so, land systems should be understood and modeled as open systems with large flows of goods, people, and capital that connect local land use with global-scale factors.

land change | forest transition

Land changes are cumulatively a major driver of global environmental change (1). In extent, the most important form of land conversion is an expansion of crop and pastoral land in natural ecosystems. During the 1980–2000 period, more than half of the new agricultural land across the tropics came at the expense of intact forests, and another 28% came from disturbed forests (2), raising concerns about environmental services and biotic diversity globally. Two strategies are commonly proposed to control this expansion and therefore promote nature conservation and its benefits: land use zoning and agricultural intensification. Various land use zoning schemes allocate land to restricted uses to ensure that valuable natural ecosystems are not converted. Intensifying agriculture, in contrast, is thought to spare land for nature because higher yields decrease the area that needs to be put under agriculture to reach a given production level. Implementation of these two strategies is generally considered to be under the control of national policies, at least as they are treated in land use change modeling and policy formulations. The acceleration of economic globalization in tandem with a looming scarcity of productive land globally may render the above strategies less effective in promoting land uses that enhance food production while preserving ecosystems, especially tropical forests.

Globalization increases the worldwide interconnectedness of places and people through markets, information and capital flows, human migrations, and social and political institutions. Over the last 300 y, the world economy has experienced an increasing separation between the location of production and consumption. Enabled by trade liberalization, progress in transport technology, and the information technology revolution (3), the cross-border trade in food commodities increased more than fivefold from 1961 to 2001, and the trade in all raw wood products increased sevenfold (4). These increases were registered by those in total and per capita volumes of freight movement, and in the proportion of freight moving over very large distances (5).

Agricultural intensification or land use zoning in a country may trigger compensating changes in trade flows and, thus, affect indirectly land use in other countries. Between 2000 and 2005, tropical deforestation was positively correlated with urban population growth and exports of agricultural products (6), except in sub-Saharan Africa. Urban and wealthy nation consumers have higher consumption levels than rural inhabitants in tropical regions where agricultural expansion takes place, thus increasing the level of production stresses there. Economic globalization also increases the influence of large agribusiness enterprises and international financial flows on local land use decisions, in some cases weakening national policies intended to promote a public good. However, trade also carries the potential to increase global land use efficiency by allowing for regional specialization in land use and productivity increases as a response to a global shortage of productive land.

This paper analyzes the challenges and opportunities for preserving natural forest ecosystems while enhancing food production in tropical developing countries under conditions of scarcity of unused productive cropland and economic globalization. It does so by drawing on examples from a few developing countries that have succeeded in increasing simultaneously their forest cover and agricultural production. These successes suggest that designing policies to reconcile development with nature conservation requires understanding land change as part of global-scale, open systems.

Conceptual Framework

The area available for nature conservation can be represented as:

$$\text{Land for nature} = \text{Total land area} - (\text{Agricultural area} + \text{Settlements}) \quad \textbf{[1]}$$

This view asserts that to maximize the land allocated for nature conservation, the land area used to produce agricultural output must be minimized (7), taking into account geographic variations in ecological attributes, land quality, and the availability of production factors. At a global scale, the demand for a given agricultural product should be equal to its supply. The required agricultural area is given by the global food equation (8), for a product i:

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SUSTAINABILITY SCIENCE

$$\text{Population} \times (\text{Consumption per capita})_i \equiv \text{Agricultural area}_i \times \text{Yield}_i \quad [2]$$

On the supply side, one food product can be replaced by substitutes that decrease the consumption of product *i* (e.g., seafood or crops with high calories per unit of cultivation). Moreover, for a country *c*, imports and exports of that product *i* affect its supply:

$$\text{Population}_c \times (\text{Consumption per capita})_{ci} \equiv \left[(\text{Agricultural area}_{ci} \times \text{Yield}_{ci}) + (\text{Imports}_{ci} - \text{Exports}_{ci}) \right] \quad [3]$$

The demand side of the equation is unlikely to decrease anytime soon as the world population will not stabilize before the second half of the century and consumption per person increases as billions of people move out of poverty (9). Replacing starchy staples by livestock and horticultural products in the food mix increases demand for land. On the supply side, the global aggregate yield increase was 1.1% on average between 1990 and 2007 (10). Future yield increases will have to first compensate for the prime agricultural land that is converted to other land uses (e.g., settlements; ref. 11) before meeting the increasing demand for food. Countries with sparse land reserves will have either to increase their imports and decrease their exports of food, feed, and fibers to preserve wildlands or acquire land abroad.

Land, an Increasingly Scarce Resource

At a global scale, land is becoming a scarce resource, asserting the need for more efficient land use allocation and innovation in agriculture. We summarized various estimates and scenarios of global land use for the 2000–2030 period (Table 1), retaining low and high estimates based on an expert judgment (*SI Text*). Of the total ice-free land area (13,300 Mha), ≈4,000 Mha is suitable for rain-fed agriculture. The noncultivated area that is suitable for cropping while being nonforested, nonprotected, and populated with <25 persons per km^2 is estimated at 445 Mha globally (12). This land reserve is mostly concentrated in Latin America's cerrados and grasslands (Brazil, Argentina) and in African savannas (Sudan, Democratic Republic of the Congo, Mozambique, Tanzania, Madagascar). Although it is not forested, converting this land to agriculture will generate environmental and social costs because it is generally rich in biodiversity and used, for example, by agro-pastoralists. The collapse of the Soviet Union resulted in the abandonment of ≈26 Mha of farmland (in Russia, Belarus, Ukraine, Kazakhstan) that is progressively being reclaimed. The land actually available for agricultural expansion in these examples will depend on future prices for agricultural products.

Different land uses will be competing for the available land (Table 1; the sources and assumptions for the figures below are described in *SI Text*). Feeding a growing world population may require an additional 2.7–4.9 Mha of cropland per year on average. The actual amount will depend on future diets, food wastages, and food-to-feed efficiency in animal production (13). In 2007, production of the feedstocks for the current generation of biofuels required ≈25 Mha. Meeting the current policy mandates of petroleum substitution by biofuels would require an increase by 1.5–3.9 Mha per year. Pasture areas are projected to only increase by 0–5 Mha per year because of an intensification of livestock production systems. The land footprint of cities is <0.5% of the Earth's total land area but urbanization is predicted to cause the loss of 1.6–3.3 Mha per year of prime agricultural land. Demand for industrial forestry will grow by 1.9–3.6 Mha per year, mainly in Asia and subtropical regions. Industrial forestry may replace natural forests but will also encroach on agricultural land. Protected areas will continue to expand by 0.9–2.7 Mha per year. Land degradation negatively affects land productivity and makes ≈1–2.9 Mha unsuitable for cultivation per year, with a high rehabilitation cost. All of the above future land demands are of the same order of magnitude. Climate change will affect agriculture directly through changes in agroecological conditions (14), potentially opening or closing lands for cultivation. Geographic shifts in land suitability will not affect all prime lands, thanks to adaptations of farming systems, but interannual fluctuations in crop yields will probably increase.

Accounting for some unavoidable deforestation, the range in availability of land suitable for cropping by 2030 might be –44 Mha to +223 Mha (Table 1). With an additional total land demand of 9.5–26.4 Mha per year, the current land reserve could be exhausted as early as in the late 2020s and at the latest by 2050. A better land accounting should be spatially explicit to reflect geographic variations in land attributes and production systems. Market responses associated with land scarcity are likely to stimulate the future adoption of more efficient land management practices. Innovations that could be a source of discontinuities in future land use trajectories and, thus, prevent a global land shortage include technological breakthroughs on genetically modified crops or second generation biofuels, investments for restoration of degraded lands, adoption of more vegetarian diets in rich countries, strict land use planning to preserve prime agricultural land, or new industrial processes to produce synthetic food, feed, and fibers. Absent such innovations, humanity could inadvertently cross a threshold where annual increments in global food production beyond yield increases would lead to an accelerating conversion of natural forests, with detrimental environmental impacts, and to cropland expansion on unsuitable lands, therefore requiring large capital investments, intensive use of water and fertilizers, and a much larger area for any increment in production.

Table 1. Estimates of land use in 2000 and additional land demand for 2030

Land use category	Low, Mha	High, Mha
Land use in 2000		
Cropland	1,510	1,611
Pastures	2,500	3,410
Natural forests	3,143	3,871
Planted forests	126	215
Urban built-up area	66	351
Unused, productive land	356	445
Projected land use for 2030		
Additional cropland	81	147
Additional biofuel crops	44	118
Additional grazing land	0	151
Urban expansion	48	100
Expansion industrial forestry	56	109
Expansion of protected areas	26	80
Land lost to land degradation	30	87
Total land demand for 2030	285	792
Balance (unused land in 2000 – land demand in 2030)		
With no deforestation	+71	–347
Clearing of natural forests	152	303
With deforestation	+223	–44

These values were derived from the literature and selected based on an expert judgment, evaluating the realism of underlying assumptions, looking for a convergence of evidence, and using 2000–2010 observations as a reality check (references and explanations in *SI Text*). The low estimates represent a conservative view of both land reserve and additional land demand, whereas the high estimates represent a slightly bolder view.

Influence of Globalization on Land Use Change

Addressing global land availability is made more complex by the processes of economic globalization. In particular, cropland expansion and forest conversion are accelerated by global-scale spatial dynamics caused by the displacement, rebound, cascade, and remittances effects.

Displacement (or Leakage) Effect. Displacement of land use from a place occurs when there is a migration of activities to another place, therefore causing land change in the other locality. Leakage is a form of displacement due to land use policies aimed at reducing environmental pressure in a place. Land use zoning for nature conservation in a country may displace population and land use within that country or abroad, via migrations or by increasing imports of agricultural or wood products, thus shifting pressure on natural ecosystems elsewhere. When it is verified, the environmental Kuznets curve—i.e., a virtuous circle between economic growth and environmental quality beyond a particular level of per capita income—is in part explained by a spatial displacement of environmental costs to other territories (15). Trade redistributes environmental impacts of policies and economic activities at the global scale (16) because it is associated with virtual exchanges of natural resources embodied in commodities being traded—e.g., water, biomass, and land use (17, 18). International trade plays a rapidly increasing role in matching supply and demand for biomass-related products (19). Accounting for trade balances in land use quantifies both the land area appropriated by production abroad through imports, and the domestic land area embodied in exports (20). In 1994, 35% of food consumption needs in Sweden were satisfied based on agricultural areas outside the country (21). In 2001, the agricultural products imported by Switzerland corresponded in virtual land to more than 150% of the arable land cultivated in the country (20).

Countries apply different levels of land use restrictions to protect or conserve nature and its services, from strict nature reserves to protected landscapes. Protected areas are suspected to accelerate deforestation in their surroundings by displacing human populations or extraction activities outside reserves, by increasing the density of agents attracted by economic opportunities around parks (22), or through land market feedbacks (23). Forests are also assigned to different forest exploitation regimes specified by law. Restricting land use may “force the marketplace to look elsewhere to satisfy material needs . . .” (24), unless demand for agricultural and forest products is shrinking because of a decrease in consumption or a substitution by other goods. Displacement of forest exploitation is a concern for climate change policies and carbon markets involving land use. With carbon crediting for afforestation and reforestation—as in Kyoto Protocole’s Clean Development Mechanism—and avoided deforestation—as in the “Reducing Emissions for Deforestation and forest Degradation” (REDD) policy—the market creates an incentive for a leakage of timber harvest and deforestation from signatory countries to nonparticipatory countries. Such a negative externality would cause a loss of net carbon benefits (25). Leakage from developed to tropical countries may be detrimental to the environment because of the latter’s overall weak environmental protection, logging practices that cause high collateral damages (26), and lower crop yields (27). Tropical forests have higher carbon densities but lower densities of commercial species (28), a richer biodiversity, and a greater role in mitigating climate warming (29) than higher latitude forests. Forest conservation in developed countries may therefore result in an “illusion of preservation” (30).

Evaluations of the effectiveness of protected areas show that rates of deforestation are much lower inside compared with outside reserves (31). Studies in Costa Rica (32) and Sumatra (33) did not find evidence for a spatial spillover effect in the neighborhood of protected areas. A reduction of deforestation in adjacent unprotected areas was observed in Sumatra, probably due to urban migrations (33). By contrast, a study in the Peruvian Amazon (34) found that, although forest concessions experienced a large reduction in deforestation after enactment of stringent timber harvest legislation, the rates of forest clearing and disturbance outside concessions increased rapidly. Protection of public forests in the US Pacific Northwest also displaced timber harvests on private timberlands in the region and further away, with a total displacement of 84% of the reduced public harvest timber because of conservation programs (35). A similar leakage effect was found for cropland in the United States, where the purchase of conservation easements on farmland brought noncropland into crop production elsewhere, for ≈20% of the cropland area that was retired from cultivation (36).

Several studies also demonstrate strong cross-border leakages. Between 1990 and 2004, developed countries that enacted conservation set aside policies increased their cereal imports per capita by 42.2% compared with an average 3.5% increase for countries that did not enact such policies (37). An economic modeling study estimated that protecting 20 ha of forests from harvest in North America and Europe induces the logging of ≈1 ha of primary forest in remote tropical places or in Russia (38). A general equilibrium model showed that forest conservation and environmental protection in countries with a significant forestry sector would be associated with a leakage—mainly to developing, tropical forest countries—of at least 65% of the timber stock being protected locally (39).

Increasing demand for wood products and new forest conservation programs in China and Finland have increased pressure on forests in neighboring Russia through wood imports (40). In the 19th and early 20th centuries, the shift from net deforestation to net reforestation—referred to as the forest transition (41)—that took place in Europe and New England was facilitated by imports of timber and food: For every region with cropland abandonment and forest regrowth, other regions experienced compensating cropland expansion and forest clearing (42, 43). Importing wood products is the economic equivalent of exporting ecological impacts (40). The national-scale reforestation of Vietnam since 1992 was achieved by the displacement of forest extraction to other countries equivalent to 39% of the regrowth of Vietnam’s forests from 1987 to 2006 (44). About half of these wood imports were illegal. For most of the developing countries that recently experienced a forest transition, displacement of land use abroad accompanied the local reforestation (45). Additional global land use change embodied in their wood imports did offset 74% of their total reforested area, a figure that is reduced when taking into account their exports of agricultural goods. Economic globalization thus facilitates a forest transition in some countries through a displacement of demands overseas, but other countries absorb these demands and undergo large-scale agricultural expansion (45). In Latin America, increasing global food demand accelerates deforestation in high potential areas for intensive agriculture while marginal agricultural lands are abandoned (46). Brazil is facilitating forest regrowth elsewhere by contributing massive quantities of beef, soy, and timber to national and global markets (42), which makes the 2004–2010 decrease in deforestation in the Brazilian Amazon even more remarkable.

Displacement of land use is also taking the form of large-scale, cross-border land transactions that are carried out by transnational corporations and sometimes initiated by foreign governments (47). In this “land grab,” large agribusiness companies from countries rich in financial capital but poor in suitable land for agriculture are acquiring large tracts of land in countries with land reserves. In 2009, >50 Mha of farmland in Africa had been subject to recent negotiations or transactions of this kind, mostly with investors from oil- or capital-rich but food-poor Asian countries (48). The food and biofuel production grown on these plots is destined for export. This off-shore agricultural production is a result of the globalization of trade, liberalization of land markets, and the expansion of direct foreign investments in the agricultural sector (47).

Rebound (or Take-Back) Effect. The rebound effect refers to a response of agents or of the economic system to new technologies or other measures introduced to reduce resource use. An increase in production efficiency lowers the cost of consumption of a good. Because of a lower price, more income available to spend, product substitutions, and an economy-wide effect through economic growth, the consumption of this good or of other goods and services increases, thus offseting the beneficial effects of the new technology (49, 50). A strong rebound effect is more likely in large and expanding markets with a potential for economic growth. Jevons (51) had already observed that technological improvements in 19th century England that led to an increase in the efficiency of coal use caused an increase rather than a decrease in coal consumption in most industries (the "Jevons paradox").

It is often assumed that intensifying agriculture will spare land for nature as, for a fixed demand, higher yields decrease the area that needs to be cultivated. However, more efficient agriculture is likely to be more profitable and could lead to an expansion of the cultivated area (52). In the short term, the magnitude of this direct rebound effect depends on the price elasticity—the ratio of the percentage change in resource demand to percentage change in resource price. If demand for a good is relatively elastic, the price decline expected from more efficient technologies will stimulate more demand. If demand is inelastic, a rebound effect can still take place through product substitutions. Although the demand for staple crops for human consumption is relatively inelastic (8), the global demands for biofuels, meat, and luxury goods such as coffee are elastic. In the long term, the magnitude of the rebound effect depends on the impact of technological progress on economic and population growth. A similar rebound effect in wood consumption can be associated with an intensification of silvicultural practices.

Aggregate global scale data suggest that past agricultural intensification did spare land for nature. If crop yields would have remained constant since 1961, an additional 1,761 Mha of cropland would have been required to achieve the same production level as in 2005 (53). This cropland expansion would have consumed all of the land reserve and caused massive deforestation. Absent agricultural intensification, large food producing countries would have required two to three times more cropland area to meet current food demands (54). These estimates ignore, however, a possible rebound effect as, with lower crop yields, food prices and mortality due to malnutrition would have been higher in the past decades, and meat consumption lower, as these variables are largely endogenous.

Cross-country data show that paired increases in yields and declines in cropland occurred infrequently during the 1990–2005 period (37), thus refuting the land sparing hypothesis. Nations with concomitant rising yields and diminishing or static cropland were characterized by land set-aside programs and increasing imports of cereals per capita (37)—thus showing a rebound effect through displacement in the latter case. Another study detected a weak land sparing effect for staple crops in developing countries: Only in this case did per capita cropland area decrease slightly with crop yield increases (55). The relationship was reversed in developed countries, where agricultural subsidies maintained a high level of production. The land sparing effect was nonexistent when all crops were taken into account, as nonstaple crops replaced staple crops when they were contracting (55). Such relationships may be confounded by population growth and food imports.

Intensive agriculture often fails to spare land for nature due to environmental off-farm impacts, displacement of marginal farmers toward the extensive margin, and in-migration of landless farmers attracted by the economic opportunities created by intensification (56). National and local scale studies show two contrasting effects of agricultural intensification on land conversion, depending on how the new technologies affect the labor market and migration, whether the crops are sold locally or globally, the profitability of farming, and the capital and labor intensity of the new technologies (52). In cases that mostly involved crops consumed locally, agricultural intensification relieved pressure from the land, leading to abandonment of slash-and-burn cultivation on steep slopes in uplands as lowlands were irrigated more intensively (57, 58). In other cases involving cash crops for rapidly expanding global markets, agricultural intensification encouraged more cropland expansion, as observed for soybean in Brazil (59, 60) and oil palm in Indonesia and Malaysia (61). Intensification based on mechanization and chemical-based weed control frees up labor that may migrate and convert more land to low-input agriculture (52, 57, 62). Profits and government subsidies associated with intensive agriculture may also be reinvested by agribusiness enterprises in agricultural expansion.

Cascade Effects. Land-use change is driven by multiple, interacting factors that originate from the local to the global scales, involve feedback loops, and cascades through land use systems (63). A cascade effect is a chain of events due to a perturbation affecting a system. In ecology, it refers to a series of secondary extinctions triggered by the primary extinction of a key species in an ecosystem. In land change, it occurs through indirect land use changes, a crucial issue when evaluating environmental impacts of biofuels, for example. The mechanism is similar to that of land use displacement, with an initial change in land use allocation causing multiple crop substitutions and land conversion in a place distant from the biofuel production site, thus leading to additional environmental effects that are not immediately measurable.

When a bioenergy crop replaces a natural ecosystem, there is a direct land conversion. When it replaces a food crop in a field already under cultivation, or when crop production is diverted from the food market to the bioenergy market, the supply of the food crop decreases—e.g., for corn, sugarcane, potato, or wheat used for ethanol, or palm or rapeseed oil used for biodiesel. The market price for the replaced crop increases, thus causing more land to be allocated to that crop (64), which could negate climate benefits from biofuels. Successive market responses trigger a cascade of crop-by-crop substitutions, which eventually cause land conversion at the margins and a loss in ecosystem services (e.g., carbon storage and sequestration potential). When cultivation expands on abandoned croplands, there is still an ecological loss as natural vegetation regrowth on these areas is prevented (64).

Indirect land-use changes are caused by the competition for prime croplands, the international trade in agricultural commodities, and agronomic innovations facilitating crop substitutions under specific agroecological conditions. Estimating the magnitude of indirect land-use changes requires simulation experiments with global economic models to isolate the impact of an expansion of bioenergy crops from other underlying causes of forest conversion (63). These models estimate production functions and price elasticities based on sparse data (65). Rules for land use allocation and conversion factors between the cropland area allocated to biofuels and the conversion of natural ecosystems need to represent such complexities as how much marginal land is used, the adoption of land-saving techniques such as multicropping, the use of crop wastes and residues as feedstocks or animal feed, and changes in consumption and yield increases induced by higher food and feed prices. New infrastructures, and traceability and certification systems for biofuels, will also affect decisions leading to indirect land use changes.

In Brazil, soybean production for food and feed markets has greatly increased. Soy is also a source of biodiesel. Sugarcane ethanol is an important transportation fuel. These evolutions raise questions on the role of these crops in causing indirectly deforestation in the Amazon basin. Pasture expansion is the dominant cause of deforestation in the Brazilian Legal Amazon. In Mato Grosso, direct conversion of forest to cropland increased during 2001–2004 (66) and soybean expanded in areas previously occupied by pastures (67). Unless pasture area decreased overall, these land use trends suggest that soybean could have displaced pastures into the Amazon, thus indirectly causing deforestation in a classic pattern of frontier expansion based on land rents. More indirectly, soybean cultivation is stimulated by infrastructure improvements (59). Ranchers that are selling their land to soy farmers at high prices appear to reinvest their capital in forested areas (60), although direct empirical links between ranch-to-soy and new ranch lands is lacking. A modeling study, however, projected that, in Brazil, sugarcane ethanol and soybean biodiesel pushing the rangeland frontier into the Amazonian forest would be responsible for ≈40% and 60%, respectively, of the indirect deforestation by 2020 (68). Rangelands would also expand following their displacement from high to low productivity lands. The surge of deforestation in the Brazilian Amazon during 2002–2004 was also related to pasture and soybean expansion in response to international market demand. Health concerns in Europe have increased demand for open-range, grass-fed cattle, and nongenetically modified soy as a source of high-protein animal feed (60). Rapid economic growth in China and a diet richer in meat products has increased soy imports from Brazil to feed pork and poultry (69). These cascade effects link land use changes in a region to events taking place in remote locations through international trade in agricultural commodities. These links work both ways: Pressures by environmental groups and consumers in distant countries recently led to moratoriums by exporters and international retailers on trade in soybeans and beef from land recently deforested.

The first model-based estimate of indirect land use change quantified that, over a 10-y period, allocation of 12.8 Mha of corn to produce ethanol in the United States would lead to the conversion of 10.8 Mha to cropland in the world (64). Subsequent studies estimated a lower, but significant, worldwide increase in cultivated land associated with US-based maize ethanol at the 2015 mandated level—e.g., 3.8 Mha (70). Conventional biofuels that European Union Member States have planned for 2020 are projected to lead to 4.1–6.9 Mha of indirect land use changes (71). Global land use scenarios for the 21st century predicted that indirect land use changes due to biofuels expansion could be responsible for up to twice as much carbon loss as direct land use for biofuels (72). The fraction of additional land conversion causing deforestation will largely depend on forest protection policies. Another integrated global model estimated a knock-on leakage (or cascade) effect of agricultural expansion on deforestation causing an additional 30–50 Mha deforestation by 2030 when biofuels were introduced (73). Another study simulated a net expansion of cultivated area in 2000–2030 of 19–44 Mha in response to additional demand for crop-based biofuel feedstocks, causing up to 24 Mha of additional forest conversion (74). A fivefold increase in the use of biomass for energy provision would almost double the present human appropriation of biomass at the global scale through wood and crop harvests, and grazing (75).

Remittance Effect. Outmigration from rural regions affects land use through a decrease in labor force and in consumption needs, and an inflow of remittances. In 2009, 214 million international migrants in the world were sending back home an estimated 414 billion US$ as remittances (76). This massive transfer of funds may facilitate the reconversion of family members at home to the rural nonfarm economy, thus decreasing pressure on land. An increase in wealth of rural households is generally associated with a decreased engagement in agriculture and diversification toward rural nonfarm activities (77). Alternatively, remittances can favor investments in mechanization and agricultural intensification. Migrants also directly purchase land in their home country, as a safety net and to maintain ties with their place of origin (47). Outmigration affects how land use decisions are made and may give rise to "remittance landscapes" (78). Migrations interact with other factors associated with globalization that trigger a structural transformation of rural areas through land privatization, access to credit, nongovernmental organizations promoting social or environmental agendas, encroachment of largeholders or infrastructure projects (e.g., dams, mines, parks) on communal land, social mobility and expanded social networks, and the growth of urban aspirations. These trends result in a diversification of land use, with new crop varieties, home gardens, niche market production, or ecotourism, and the growth of off-farm activities (79).

Evidence on the effects of remittances on land use is sparse. In Vietnamese coastal communities, remittances were invested primarily in education, thereby increasing access to nonfarm income, but also in consumption, livestock, and agricultural diversification (80). In El Salvador, forest recovery was not correlated with local rural population density but with remittances sent from abroad by family members. Households with remittances cleared less forests (81). In the highlands of Ecuador, outmigration and remittances were not associated with a decline of agriculture or with landesque investments. Rather, subsistence agriculture continued to be a culturally valued and risk-averse activity (82). People having migrated abroad from southern Morocco invest more in land in their place of origin and have more formal property rights than households living in the area (83). The effects of remittances depend on the characteristics of the migrants and on the local agrarian system (84). Outmigration alone rarely leads to land abandonment, but rather to an extensification of land use (85), especially in "hollow forest frontiers" where sustained, profitable land uses have yet to emerge (86).

Success Stories of Land Use in the Globalization Era

The dynamics detailed above have led to pressures on forest lands in the developing world, especially in the tropics, generating concerns about the environmental impacts of deforestation, both global and local. The prognosis may appear to be dire, but various proposed practices and evidence from a few countries demonstrate that appropriate policies can lead to national-scale land use transitions, spare land for forests, deal with the impacts of globalization and, therefore, prevent a conversion of all available land.

Land Use Integration vs. Specialization. Two contrasted— but not mutually exclusive—approaches have been proposed to manage future land use (87): One attempts to reconcile production with ecosystem conservation locally through nature-friendly farming, whereas the other one separates them further through regional land use specialization. In the former, on-farm practices can be made more benign to natural ecosystems through a reduction in chemical inputs and retention of patches of nonfarmed areas and farmed seminatural habitats in the matrix of farmed landscape, and by maintaining biodiversity in low-intensity farming systems (87, 88). In the developing world, tree cover can be maintained on a landscape with fruit orchards, wood lots, agroforestry systems, gardens, hedgerows, and secondary successions on fallows (89, 90). These wooded landscape mosaics often develop at forest margins, with forest fragments and patches of intensive farming. Smallholders in rural areas actively manage the multifunctionality of these ecosystems and extract nontimber forest products (89). These tree-based land use systems have a conservation value despite a different composition and structure compared with primary forests (7).

In the land-use specialization view, nature and intensive agriculture are segregated spatially. When marginal regions are integrated into international labor markets, they benefit from new niche markets and environmental policies (91, 90), with positive impacts on ecosystems and livelihoods. International trade can improve the spatial adjustment between land use and the productive potential of regions (41). The globalization of the agricultural and forestry production systems therefore has the potential for relieving pressure from marginal ecosystems (9) as a regional specialization in the locally most appropriate land uses increases the global efficiency of land use. Differences in the availability of productive space, labor costs, and environmental legislation also drive a reallocation of land use. Productivity gains in agriculture and forestry, trade in land-based products, and displacing production from marginal to high potential regions is not a zero-sum game and can spare land for nature. Increasing deforestation locally in high potential areas could thus be beneficial at the global level (8). Access to global markets may also accelerate the diffusion of sustainable land management practices.

Learning from Recent Forest Transition Countries. A few developing countries have recently achieved a land use transition with a simultaneous increase in food production and forest cover: China, Vietnam, India, Bhutan, Costa Rica, El Salvador, and Chile (92). Understanding the conditions associated with these land use transitions is rich in policy lessons. The four cases (China, Costa Rica, El Salvador, Vietnam) that most clearly qualify as recent forest transition countries (Fig. 1 and Table 2) experienced a growing total population, with a decreasing or stable rural population, except for Vietnam, where agriculture still contributed a large share of the GDP. Crop yields, and crop and meat production, increased and the total agricultural area expanded, except in Costa Rica. Thus, forests did not encroach mainly on prime agricultural land but rather on abandoned or marginal land. Protected areas have generally expanded, mostly in Costa Rica and China. Forest reserves and other forms of zoning of forestry land helped to control the rebound effect of agricultural intensification. Forest plantations contributed a large share of the expanding forest cover in Vietnam and China. The roundwood production in these countries declined or remained stable. All these countries displaced some of their land use abroad as they were going through a land use transition (45). Most countries increased their imports of wood products and meat while shifting from net exporters to net importers of agricultural products. This shift caused cascade effects on land use systems abroad; e.g., China increased its imports of soybean from Brazil, with possible indirect effects on deforestation. China also outsourced part of its land use through large-scale land transactions in Africa. In Costa Rica, foreign private agents invested financial resources in nature conservation (93), whereas in El Salvador, remittances sent by migrants living abroad facilitated forest recovery (81).

The land use transition in these countries has thus been achieved through multiple interacting mechanisms including agricultural intensification, land use zoning, forest protection, increasing reliance on imported food and wood products, and foreign capital investments. The pathways leading to a land use transition rely to various degrees and combinations on off-farm employment, land use diversification by smallholders, state intervention in land management, and integration in the global economic system (92). Forest cover expansion is associated with various mixes of natural forest regeneration and plantations of exotic tree species, with a lower ecological value in the latter case. Numerous developing countries with conditions similar to that of the seven recent forest transition countries, however, have not achieved a net reforestation. Systematic analyses of these cases have not been undertaken. Pending them, a cautious assessment holds that forest transitions are highly contingent and not necessarily an inevitable consequence of economic globalization and modernization.

The global food equation (Eq. **3**) identifies the conditions for a global-scale forest transition. Each intervention option must be evaluated for its land-saving and other environmental impacts. Productivity increase only spares land for forests if it does not stimulate more demand for land-intensive commodities via the rebound effect. Substitutions of goods often displace environ-

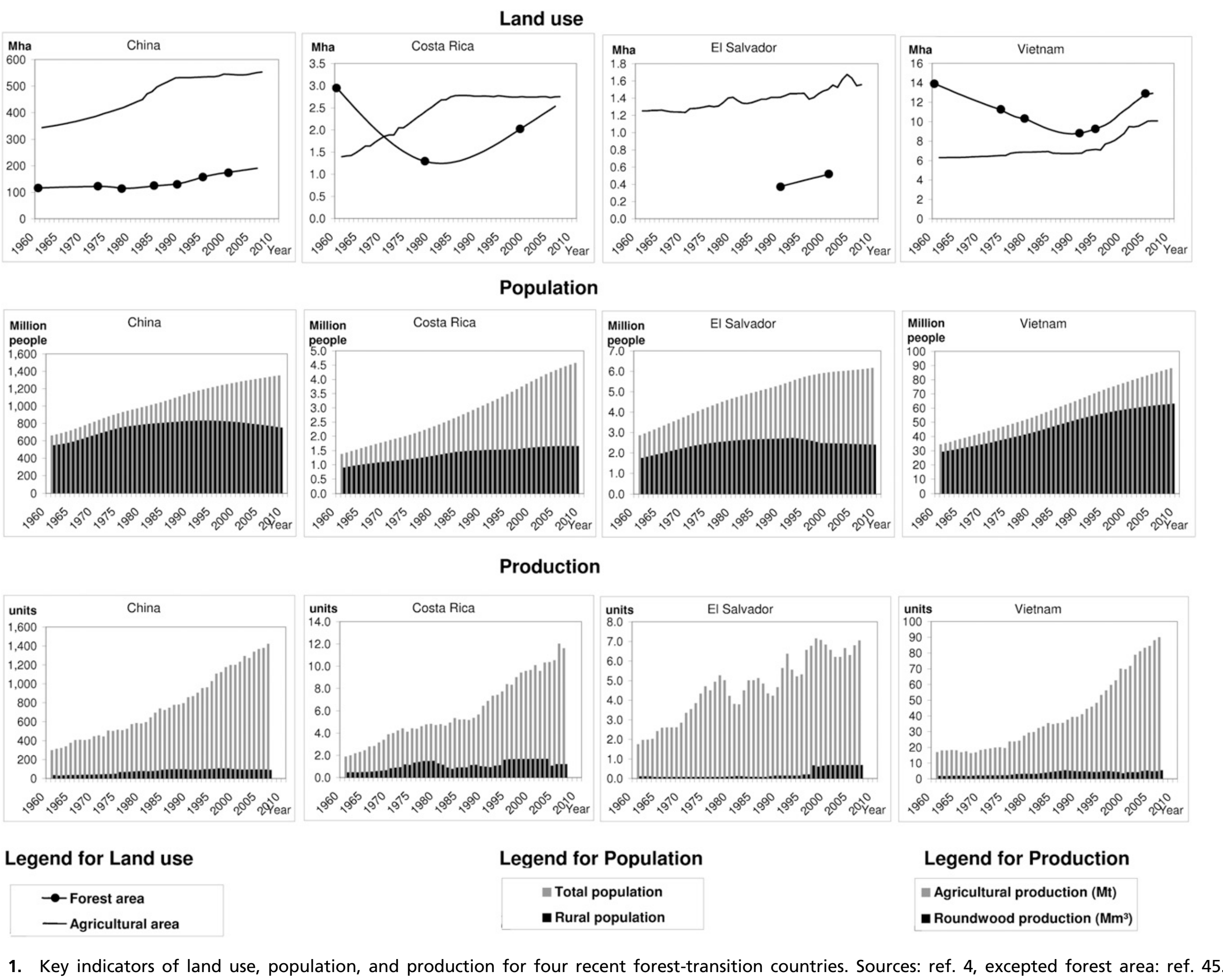

Fig. 1. Key indicators of land use, population, and production for four recent forest-transition countries. Sources: ref. 4, excepted forest area: ref. 45. Agricultural production includes crop products and meat.

Table 2. Key land use variables for four recent forest transition countries

Indicator	China	Costa Rica	El Salvador	Vietnam
% GDP from agriculture (2008)	11	7	13	22
% reforestation by plantations (1990-2005)*	23.8	0.4	0	44
% crop yield increase (primary products, 1961–2007)*	3.03	3.00	2.57	2.05
Protected areas (% of land area)†	16.6	20.9	0.8	6.2
Foreign investments in land use (% of total FDI, 2006)‡	1	2.2	0	3
Land deals in Africa (10^3 ha)§	7,308	0	0	10
Remittances (% of GDP, 2008)¶	1.1	2.0	17.2	7.9

*Food and Agriculture Organization of the United Nations (4).
†International Union for Conservation of Nature and United Nations Environment Programme-World Conservation Monitoring Centre (95).
‡United Nations Conference on Trade and Development, FDI/TNC database (96).
§Global Land Project (48).
¶World Bank.

mental impacts across sectors (e.g., from land to oceans with a shift from meat to fish; from land to atmosphere with a shift from wood to cement). Outsourcing land use globally is not an option, but a cross-border displacement of land use that moves production to more productive lands and improves efficiency of land use is favorable for forest area, although transport is a source of pollution. Demand will continue to rise but could shift toward commodities that save land (e.g., away from meat) and that are associated with sustainable land use practices (e.g., as certified through labeling schemes).

Conclusion

Economic globalization combined with the looming global land scarcity increases the complexity of future pathways of land use change. Predictions of the expected land use impact of national policies have become more uncertain. In a more interconnected world, agricultural intensification may cause more rather than less cropland expansion. Land use regulations to protect natural ecosystems may merely displace land use elsewhere by increasing imports. Mitigating climate change by mandating the use of biofuels in one place may increase global greenhouse gas emissions due to indirect land use changes in remote locations. A decrease in rural population due to outmigration may increase land conversion through remittances being invested in land use.

Despite these vexing mechanisms, a few developing countries have recently managed to navigate a transition toward more efficient land use, through varying combinations of strategies. The apparent tradeoff between forest and agriculture can be minimized through spatial management and the use of degraded or low competition lands. Although some land use displacement is an unavoidable consequence of land use zoning, it never offsets 100% of the benefits for forest conservation—the glass remains half full. A zero-sum game in trade of agricultural and forestry products can be avoided by improving land use efficiency and the spatial adjustment between land use and the productive potential of regions. The rebound effect associated with agricultural intensification can be controlled by regulating land use, trade and consumption, e.g., through certification schemes. Global scale cascading effects of land use decisions could also be regulated through new forms of global governance linking trade with environmental protection.

Managing a transition toward more environmentally efficient and, thus, more sustainable land use involves better information on the global scale impacts of land use decisions, the creation of appropriate incentives for agents, and a greater capacity to adopt new land use practices (94). A more efficient land management and major technological innovations in agriculture have the potential to prevent a global shortage of productive land. In short, yes, "it's globalization, stupid," but its effects on land use can be harnessed if land use is understood as being part of open and complex human-environment systems dominated by long distance flows of commodities, capital, and people. The possibility of a global land use transition with a concomitant increase in agricultural production and forest area remains to be investigated.

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Supporting Information

Lambin and Meyfroidt 10.1073/pnas.1100480108

Land, an Increasingly Scarce Resource

Cropland and Pastures in 2000. The low estimates come from Ramankutty et al. (1) and the high estimates from FAOSTAT (2). The figures for cropland include arable land and permanent crops (shrubs and tree crops). They include temporary fallow lands (<5 y) and cultivated land that may be underused, but exclude abandoned land resulting from shifting cultivation. Pastures include permanent meadows, pastures, and grasslands used for grazing.

Natural and Planted Forests in 2000. The low and high estimates of forest cover come from a remote sensing study (3) and the successive estimates by FAO Forest Resource Assessment (FRA) 2000, 2005, and 2010 (4–6). The FRA 2000 includes an independent remote sensing survey of tropical forests. The lowest value for total forest cover in 2000 was the 3,269 Mha of the remote sensing study (3). The lowest value for forest plantations was the figure of 126 Mha from FRA 2005 (5). This value was subtracted from the total forest area from the remote sensing study (3) to calculate a low estimate for natural forests. The high estimates are those from FRA 2010 (6). The low estimate for plantations uses the FRA 2000 and 2005 definition of forest plantations as forest stands of introduced species, or intensively managed stands of indigenous species of even age class and regular spacing (4, 5). The high estimate uses the FRA 2010 definition of planted forests as forests predominantly composed of trees established through planting and/or deliberate seeding of native or introduced species, thus encompassing plantation forests and planted seminatural forests (6).

Urban Built-Up Area in 2000. The low estimate comes from a mapping of urban extent by using MODIS 500-m resolution satellite data (7). The high estimate is from the Global Rural-Urban Mapping Project (GRUMP) that was based on a gridded population database of cities and towns of 1,000 persons or more (8). The difference in method (remote sensing versus gridded demographic data) explains the large discrepancy between these two estimates.

Unused, Productive Land. Assessments of the global land reserve—i.e., the uncultivated but productive land—are often too optimistic as many of these areas are under natural forests, are already used as permanent pastures, are protected areas, include marginal lands (9), or are only suitable for a single crop (e.g., olive trees in Mediterranean drylands) (10). A recent World Bank report (11), based on a detailed mapping study by the International Institute for Applied Systems Analysis (IIASA) (12), estimated that the noncultivated area that is suitable for cropping while being nonforested, nonprotected, and populated with <25 people per km^2 amounts to 445 Mha globally. In our low estimate, we assume that institutional constraints—e.g., land tenure, political conflicts, traditional rights of land access—and biophysical constraints—e.g., accessibility, risks of natural hazards, ecological corridors—restrict access to ≈20% of this land reserve. Another study (9) provides empirical support to such a conservative estimate of land surplus by showing that, in developing countries, the true land reserve is more likely to be 3–25% rather than 50% of the cultivable land, as was claimed in global assessments by FAO in the 1980s and 1990s. Our high estimate of land reserve retains the value of 445 Mha of IIASA (ref. 12 cited in 11). This estimate is consistent with an older study (13) that estimated 16 y earlier that the world's arable land could be expanded at most by 500 Mha. These authors noted that the productivity of this new land would be much below present levels in land now being cropped. Note that our high estimate is an optimistic scenario as it assumes that, by 2030, every hectare of productive land in conflict-prone countries such as Sudan and RD Congo will be used.

Additional Cropland Needed. On the low end of the spectrum of estimates of additional cropland needed in the coming decades, a recent assessment (10)—based on the latest FAO food and agriculture baseline projections to 2050—estimated that 90% (80% in developing countries) of the growth in crop production by 2050 would be a result of higher yields and increased cropping intensity, with the remainder coming from land expansion. Arable land would then expand by some 70 Mha, the expansion of land in developing countries by ≈120 Mha being offset by a decline of some 50 Mha in the developed countries. From 1990 to 2005, the world's crop area expanded by 2.7 Mha per year (11). Declines in industrialized and transition countries (−0.9 and −2 Mha per year, respectively) were more than outweighed by increases in developing countries (+5.5 Mha). If that rate would remain constant, 81 Mha of cropland would be added during the period 2000–2030. On the higher end of the spectrum, a statistical study (14) produced four different extrapolations to the years 2020 and 2050 of the temporal trends since 1960 in cropland and pasture land. Additional cropland needed would be 120 Mha by 2020 and 350 Mha by 2050 (thus 197 Mha by 2030, based on a linear interpolation). Another study (15) computed that, between 2000 and 2030, ≈100–200 Mha of reserve land will be converted to cropland just to ensure a constant per capita production. A study by IIASA (16) estimated, based on a general equilibrium model, that an additional 147 Mha arable land may be required in 2030 to meet food and feed demand alone. The reference scenario of a recent study (17) projects an increase in cropland of 126 Mha by 2030. A World Bank report (11) compiled projections based on computable general equilibrium models that include price and trade mechanisms. These various models projected an increase in area cultivated by 2030 of 6, 10.2, and 12.3 Mha per year (thus 180–369 Mha by 2030). Note, however, that these figures include biofuels. Another model projection reviewed in this report computed an increase of 4.5 Mha per year (or 135 Mha by 2030) without biofuels. A model-based study on changes in ruminant production systems projected that, by 2030, a rapid intensification of livestock production systems will be associated with an increase of cultivated areas by 115 Mha for feed production only (18). The large range of the above estimates reflects uncertainties on future crop yields, food demand, and prices. We adopted a low and high estimate of 81 and 147 Mha, respectively, to capture the range of published values while ignoring the extremes.

Additional Land for Bioenergy Crops. The Gallagher Review of the indirect effects of biofuel production (19) estimated that the total requirements for land for first-generation biofuels, if all major countries and regions were to attain their stated targets to 2020, would be 56–166 Mha. Model simulations by IIASA (16) estimated that an additional 65–150 Mha may be allocated to biofuels by 2030, creating a net demand for additional cropland of 19–44 Mha given agricultural intensification and a decline in demand induced by price increases, and the land-saving effect of the use of coproducts. These scenarios assume that the share of biofuels would reach 4–10% of total transport fuel use by 2030 (it was ≈1.8% of road transport fuels in 2007). We based our low estimate on the TAR-V1 scenario of IIASA (16), which assumes that the mandatory, voluntary, or indicative targets for biofuels use announced by major developed and developing countries will be met by 2020 and that second-generation biofuels technologies will be gradually deployed after 2015. Their other scenarios assume either faster or slower deployment of second-generation technologies and/or do not integrate policy-mandated targets. The TAR-V1 scenario predicts a net additional demand for cropland of 44 Mha when biofuels are taken into account, compared with the reference scenario where biofuels use is frozen at the level of 2008. This scenario integrates market feedbacks. Our high estimate was taken from a recent study (20), which computed that the land required for meeting a targeted petroleum substitution of 10% by biofuels in 2030 is ≈118 Mha for the combination of crops with the smallest land requirement (palm oil and sugarcane). Other crop combinations would require much more land (up to 508 Mha using soybean and maize). By retaining their lowest value, we assumed that land scarcity will push the market and policy-makers to favor the least land-demanding crop combinations for bioenergy production. We thus retained a range of values of 44–118 Mha. This range assumes that there will be no new mandated targets for the period 2020–2030, which is a conservative approach.

Additional Grazing Land Needed. Our low estimate assumes no expansion of grazing systems because an intensification of livestock production systems has the potential to meet the growing demand for animal products. This estimate is in agreement with model projections on the world ruminant production systems (18) and other global land use models (21). Note that, under these scenarios, the cropland allocated to produce animal feed has to expand (+115 Mha in ref. 18). This low estimate is also consistent with the baseline scenario of the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) (22). Our high estimate is based on the reference scenario of a recent study (17) projecting an increase of 151 Mha of grazing land by 2030. It is consistent with most global land use model scenarios (21), which project an increase in grazing systems of ≈10% for 2010–2050. We ignored higher figures predicting a 25% increase in grazing systems by 2050 (21). We also ignored extrapolations of past trends that projected an additional 200 Mha of pastureland by 2020 and 540 Mha by 2050 (14). The latter estimates do not include a land market feedback that will likely be associated with an increase in global land scarcity and will create an incentive to intensify animal production, as projected in the other sources. Recent trends and model calculations suggest that most of the increase in grazing land will take place on land considered as suitable for agriculture rather than on marginal land (18).

Urban Expansion. For our low estimate, we used an estimate of a loss of prime agricultural land due to demands for land for other purposes than agriculture in less developed countries of 1.6 Mha per year, or 48 Mha between 2000 and 2030 (15). This estimate is slightly higher than the low estimate based on calculations assuming average urban population densities of middle and low income countries, and a demographic projection with falling fertility (23). Our high estimate is based on a computation assuming that the built-up area of cities will need an additional 100 Mha by 2030, taking into account different growth rates and urban population densities in developing and industrialized countries (24). This value is consistent with the high estimate of another study (23) once it is scaled to the 2000–2030 period.

Additional Land for Industrial Forestry. We took the range of several estimates of change in tree plantation area (4, 25–28) for 2030, 2040, or 2050, with base years of 1995 or 2000. Changes in the area of planted or plantation forests were recalculated for 2000–2030 based on the assumptions described in these sources. We then computed the actual change in planted forest area between 2000 and 2010 from FAO FRA 2010 (6), and the business as usual change in plantation forest area between 2000 and 2010 based on FAO FRA 2005 (5). The estimates of change for 2000–2030 that were smaller than the changes that already occurred between 2000 and 2010 were ignored. We were thus left with a range of estimate of change for 2000–2030 from +56 Mha to +109 Mha. This increase is expected to take place mainly on land formerly used for agriculture (29), although a small fraction may also take place at the expense of natural forests. Because of climatic, soil, or accessibility constraints on other land (4), most of the expansion of industrial forestry will have to occur on land suitable for rainfed agriculture. Some expansion on degraded lands that were removed from agricultural production is possible (30). However, land rehabilitation through afforestation is expected to be minimal given its high cost, the decline of many national plantation programs (4, 29), and the small share of the land suitable for afforestation that is strongly or extremely degraded (31). We therefore assumed that the amount of degraded land that was completely removed from production and would be rehabilitated through plantations is negligible compared with the total increase in industrial forestry areas.

Expansion of Protected Areas. Under the Convention on Biological Diversity (CBD), the world's governments have set a goal of protecting at least 10% of the world's ecological regions by 2010, a target that is likely to be missed. Since 2003, an average of 0.13% of the global land area—≈1.7 Ma—was added annually to the existing network of terrestrial protected areas (32). Our low estimate assumes an expansion of protected areas for the 2000–2030 period at the rate that was already observed between 2003 and 2009. It is unlikely that all these areas will compete strongly with other land uses but some will be located at forest frontiers (21). We therefore arbitrarily reduced by 50% the above number to account for noncompetitive protected areas. Our high estimate is based on the "Sustainability First" scenario of UNEP's GEO4 project (33). Under this scenario, to reach a minimum share of protected area per biome category, an increase in protected area of ≈400 Mha worldwide between 2009 and 2030 would be required. With such a large expansion of protected areas, we expect an even smaller share of these areas to compete with other land uses. We arbitrarily assumed that only 20% of these new protected areas would be located in land suitable for agriculture or forest plantations.

Land Lost to Land Degradation. Among all of the figures in Table 1, the estimate of future land degradation is the most uncertain, as estimates of past land degradation are unreliable and no credible projections have been produced so far. A widely quoted figure in United Nations and World Bank reports is that 5–10 Mha (or sometimes 5–7 Mha) of land is so severely degraded every year that it is taken out of production annually. A study in the 1990s (13) estimated that 5–7 Mha per year of cropland were lost or abandoned because of soil erosion, and another 2–3 due to salinization and waterlogging. United Nations and World Bank reports also sometimes claim that 12 Mha of the world's drylands are lost every year to desertification. It is widely believed among the scientific community that these figures overstate the case for cropland abandonment due to land degradation (34) and that the evidence supporting these very high figures is weak. A compilation of all local to regional scale studies and maps that identified recent land degradation based on reliable evidence (35) could not find the dozens of millions of hectares of severely degraded lands that used to be suitable for agriculture. Another study based on historical land use data (36) measured the global area of abandoned agriculture (crop and pasture, excluding large patches of urban areas and forests in 2000) from 1700 to 2000 to be 385–472 Mha. Approximately 36.8% of abandoned crop areas was concentrated in North America (the Eastern United States mostly) and in Europe, where past cropland abandonment was generally not due to land degradation but rather to an economic transition associated with industrialization and urbanization. The land abandonment in the remaining world's regions was thus 243–298 Mha. This study also found that 99% of the land abandonment occurred in the last 100 y, thus leading to an annual rate of past cropland abandonment in regions where land degradation might be an important cause of 2.4–2.9 Mha per year. These figures thus provide an upper bound to our estimate of land degradation. In an approach whose validity was subsequently questioned (37), an analysis of a time series of remote sensing images (38) estimated that 3,506 Mha were degrading between 1981 and 2003, or 23.5% of the global land area, most of it (78%) being—quite unexpectedly—in humid regions. In most cases, land degradation on croplands simply reduces productivity, which can be compensated by fertilizer inputs. Only a small fraction of the degrading cropland is so severely degraded that it has to be removed from agricultural production. Land restoration efforts also reclaim some of the land abandoned over the years. A different approach estimates the agricultural production potential that is being lost every year due to a decline in land quality affecting cultivated areas, because of processes as diverse as soil crusting, compaction, erosion, environmental pollution, acidification, leaching, salinization, waterlogging, fertility and depletion. A study showed that soil degradation has already had significant impacts on the productivity of ≈16% of the world's agricultural land (cited in ref. 39). This estimate was based on the GLASOD data (40) that are known to have overestimated the extent of land degradation. Another study (41) estimated total productivity losses due to land degradation on cropland and rangeland in dry areas at ≈0.3% annually. Combining these two gross estimates suggests that past land degradation on land still under cultivation could have been equivalent to losing a maximum of 0.725 Mha of cropland per year. However, the great variations in the impact of soil erosion on productivity decline between crops, soil orders, and locations make such an aggregation difficult (39). To capture these large uncertainties, we adopted estimates of the loss of land and productive potential due to land degradation equivalent to 1–2.9 Mha per year, or 30–87 Mha for 2000–2030. We caution however that there is only weak evidence to support these figures and they may still veer on the high side.

Future Deforestation. To meet future land demands, it is likely that cropland, grazing land, or planted trees will continue to expand on natural forest areas, despite the high ecological cost associated with deforestation. Some national and global scale policies are aimed at controlling forest clearing, with some success in several countries. At the global level, the net decline in natural forest area in the period 2000–2010 was estimated at 10.1 million hectares per year by FAO's Forest Resource Assessment (FRA) 2010 (6), down from 12.6 million hectares per year in the period 1990–2000. This figure includes forests converted to agricultural land and lost through natural causes. Our low estimate of future deforestation sums the deforestation that already took place in 2000–2010, half of that rate of deforestation for 2010–2020—which is the stated goal of UNFCCC's REDD program—and no net deforestation for 2020–2030. Our high estimate of future deforestation assumes that the forest area being converted every year will remain constant, leading to another 303 Mha of land being cleared by 2030. An alternative method to estimate future expansion of agriculture on forests is based on future demand and past sources of land. A recent study (42) estimated that, in the 1980s and 1990s, 83% of new agricultural land came at the expense of natural (both intact and disturbed) forests. Assuming that this rate will remain constant until 2030, 83% of our low and high estimates for additional cropland, land for bioenergy crops, and grazing lands needed by 2030 gives a range of 104–345 Mha of additional deforestation by 2030, which includes the narrower range retained here. Note that the above figures do not include the vast tracts of natural forests that are affected by selective logging, which does not affect forest area but leads to a decline in the average biomass of forests (43).

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