Supporting Information

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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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