Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems

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Human appropriation of net primary production (HANPP), the aggregate impact of land use on biomass available each year in ecosystems, is a prominent measure of the human domination of the biosphere. We present a comprehensive assessment of global HANPP based on vegetation modeling, agricultural and forestry statistics, and geographical information systems data on land use, land cover, and soil degradation that localizes human impact on ecosystems. We found an aggregate global HANPP value of 15.6 Pg C/yr or 23.8% of potential net primary productivity, of which 53% was contributed by harvest, 40% by land-use-induced productivity changes, and 7% by human-induced fires. This is a remarkable impact on the biosphere caused by just one species. We present maps quantifying human-induced changes in trophic energy flows in ecosystems that illustrate spatial patterns in the human domination of ecosystems, thus emphasizing land use as a pervasive factor of global importance. Land use transforms earth's terrestrial surface, resulting in changes in biogeochemical cycles and in the ability of ecosystems to deliver services critical to human well being. The results suggest that large-scale schemes to substitute biomass for fossil fuels should be viewed cautiously because massive additional pressures on ecosystems might result from increased biomass harvest.

biomass | global environmental change | human impact | biosphere | land use

Material flows resulting from human activities have become a major component of earth's biogeochemical cycles (1). Human alterations of photosynthetic production in ecosystems and the harvest of products of photosynthesis, often referred to as "human appropriation of net primary production (NPP)" or HANPP, have received considerable attention (2–4). NPP is the net amount of carbon assimilated in a given period by vegetation. It determines the amount of energy available for transfer from plants to other levels in the trophic webs in ecosystems. HANPP not only reduces the amount of energy available to other species (2), it also influences biodiversity (5–8), water flows (9), carbon flows between vegetation and atmosphere (10, 11), energy flows within food webs (12), and the provision of ecosystem services (13, 14).

Previous studies of NPP harvested to satisfy human needs and wants or foregone because of human-induced changes in ecosystem productivity suggested a substantial human impact on the biosphere, thus raising global sustainability concerns (15, 16). Existing global HANPP studies do not make full use of the spatially explicit databases available (12), and their results are quite diverse (2, 5, 16, 17). The estimate presented here is based on the best available global databases and integrates them in a high-resolution geographical information systems (GIS) data set. These data, in combination with a dynamic global vegetation model (DGVM), are used to derive a comprehensive assessment of global HANPP. This study localizes human-induced changes in ecosystems in a grid with 5′ geographical resolution ($\approx$10 $\times$ 10 km at the equator) for the year 2000.

HANPP results presented here are based on country-level Food and Agriculture Organization (FAO) statistics (161 countries covering 97.4% of global land) on area and biomass harvest on cropland and forests. FAO livestock statistics are used to derive a feed balance for each of these countries to calculate the amount of biomass grazed that is not reported in statistics. Potential NPP is calculated by using the Lund–Potsdam–Jena (LPJ) DGVM (18, 19), a well established biogeochemical process model of global vegetation. Actual NPP is calculated by using harvest indices to extrapolate NPP on cropland from harvest statistics, whereas LPJ is used in wilderness areas, forests, and grazing areas. On grazing areas, the effects of fertilization, irrigation, and soil degradation on NPP are explicitly included in the estimate and results are cross-checked against grazing demand. NPP consumed in human-induced fires is calculated in a detailed regional breakdown.

Results of HANPP calculations vitally depend on the definition used (2, 20, 21). We define HANPP as the combined effect of harvest and productivity changes induced by land use on the availability of NPP in ecosystems. That is, HANPP is calculated as the difference between the NPP of potential vegetation (NPP_0), i.e., the plant cover that would prevail in the absence of human intervention and the fraction of NPP remaining in ecosystems after harvest (NPP_t). NPP_t is calculated by subtracting the amount of NPP harvested or destroyed during harvest (NPP_h) from the NPP of currently prevailing vegetation (NPP_{act}) (5, 6). HANPP, thus, is the sum of ΔNPP_{LC} and NPP_h, where ΔNPP_{LC} denotes the impact on NPP of human-induced land conversions, such as land cover change, land use change, and soil degradation.

One major argument in favor of this HANPP definition is that changes in agricultural technology can result in considerable increases in NPP_{act} over time (22, 23). Harvest increases need

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Abbreviations: HANPP, human appropriation of net primary production; NPP_n, net primary production of *n*; DGVM, dynamic global vegetation model; LPJ, Lund–Potsdam–Jena; TBFRA, Temperate and Boreal Forest Resources Assessment.

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Table 1. Global carbon flows related to the human appropriation of net primary production (HANPP) around the year 2000

	Total NPP		Aboveground NPP	
NPP-related carbon flows	Pg C/yr	%	Pg C/yr	%
Potential vegetation (NPP_0)	65.51	100.0	35.38	100.0
Actual vegetation (NPP_{act})	59.22	90.4	33.54	94.8
Human-induced alteration of NPP (ΔNPP_{LC})	6.29	9.6	1.84	5.2
Human harvest (NPP_h)	8.18	12.5	7.22	20.4
Human-induced fires	1.14	1.7	1.14	3.2
Remaining in ecosystem (NPP_t)	49.90	76.2	25.18	71.2
$HANPP_{total}$	15.60	23.8	10.20	28.8
Backflows to nature*	2.46	3.7	1.50	4.2

*On-site backflows of harvested biomass to ecosystems, i.e., unused residues, harvest losses, feces of grazing animals, and roots killed during harvest.

therefore not necessarily result in a reduction in NPP_t. Thus, it is important to consider ΔNPP_{LC} so as not to neglect technological progress (24). Moreover, we prefer a not-too-inclusive definition of HANPP, in accordance with the fact that a considerable fraction of the NPP of grazing land and forest plantations actually remains in the ecosystem and supplies trophic energy to ecological food webs there. To explore the importance of issues of definition, we use our database to calculate HANPP according to the definition given by Vitousek *et al.* (2) and compare the results to those obtained with the definition used here.

Results

Human activities have a substantial effect on global NPP and its pathways through ecological and social systems. Our calculations show (Table 1) that humans appropriated ≈15.6 Pg C/yr, which represents 23.8% of global terrestrial NPP_0 in the year 2000. Because humans mostly use aboveground NPP, it is relevant from a socioeconomic perspective to consider this compartment. Here, we find an even stronger impact: aboveground HANPP amounted to 10.2 Pg C/yr or 28.8% of aboveground NPP_0. Overall, biomass harvest contributed 53% to total HANPP, land-use-induced productivity changes contributed 40%, and human-induced fires contributed 7%. A considerable amount of biomass included in NPP_h (16% of total HANPP or 3.7% of NPP_0) immediately flows back to ecosystems as roots killed during harvest, crop and wood residues remaining on site, or as feces of grazing animals and is, thus, only available for detritivorous food chains. Human biomass harvest alone is ≈12% of total NPP_0 and 20% of aboveground NPP_0.

We find significant alterations in NPP resulting from human-induced land changes (ΔNPP_{LC}). As shown in Table 1, land use has resulted in an aggregate reduction of global NPP by 9.6%, with large regional variations shown in Fig. 1*a*. Land use does not necessarily reduce NPP. Irrigated land as well as intensively used agricultural areas can have a higher productivity than the potential vegetation. The spatial distribution of total HANPP is shown in Fig. 1*b* as the percentage of NPP_0 appropriated in each grid cell. Maps of NPP_0, NPP_{act}, NPP_t, and HANPP in absolute units (g C/m^2/yr) are available as supporting information (SI) Figs. 2–5.

The maps presented in Fig. 1 show where on earth, and how strongly, humans alter ecological energy flows, thus localizing the intensity of human domination of ecosystems. Cropland and infrastructure areas are used most intensively, resulting in global average HANPP values on these areas of 83% and 73% (Table 2). HANPP is much lower on grazing land (19%) and in forestry (7%). In the global average, areas currently under forestry are

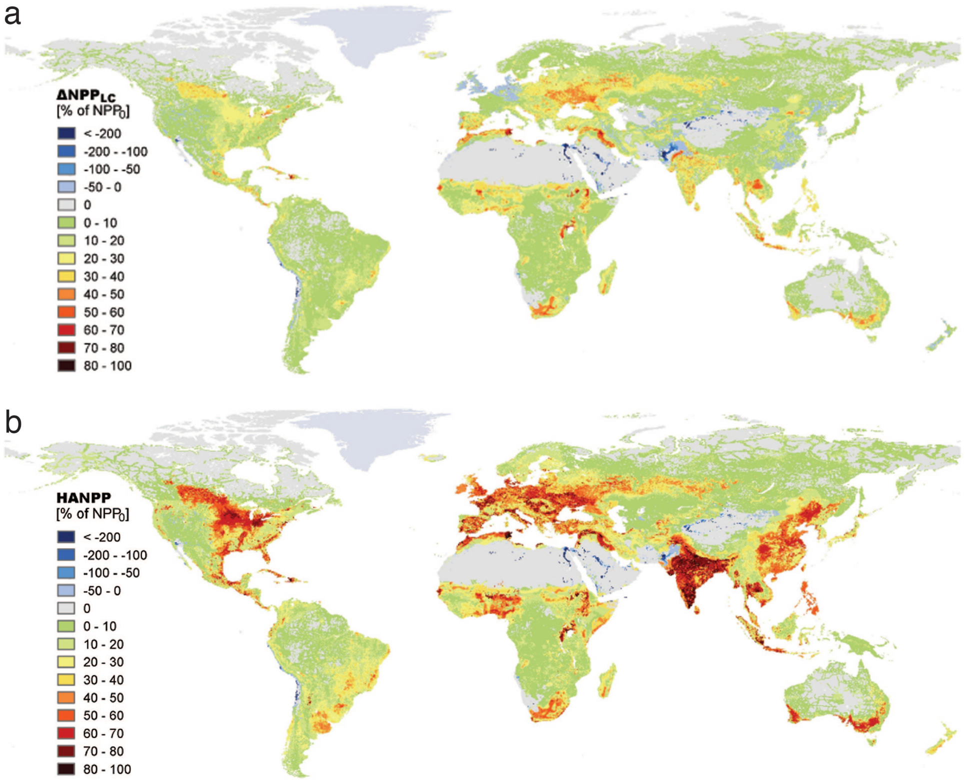

Fig. 1. Maps of the human appropriation of net primary production (HANPP), excluding human-induced fires. (*a*) Land-use-induced reductions in NPP as a percentage of NPP_0. (*b*) Total HANPP as a percentage of NPP_0. Blue (negative values) indicates increases of NPP_{act} (*a*) or NPP_t (*b*) over NPP_0, green and yellow indicate low HANPP, and red to dark colors indicate medium to high HANPP.

Table 2. Breakdown of global HANPP (excluding human-induced fires) in the year 2000 to land-use classes

Land use category	NPP_0, gC/m²/yr	NPP_{act}, gC/m²/yr	NPP_h, gC/m²/yr	NPP_t, gC/m²/yr	HANPP on this area, %	ΔNPP_{LC}, %	Contribution to total HANPP, %
Cropping	611	397	296	101	83.5	35.0	49.8
Grazing land	486	433	41	392	19.4	11.0	28.5
Forestry	720	720	48	673	6.6	0.0	10.6
Infrastructure areas	586	221	63	158	73.0	62.3	3.7
Wilderness	229	229	None	229	None	None	0.0
Global average or total	502	454	63	391	22.1	9.6	92.7*

*The remaining 7.3% are caused by human-induced fires (see Table 1).

most productive, followed by areas used today as cropland and infrastructure. The potential productivity of grazing land is lower than that of cropland, reflecting the fact that fertile areas are used for cropping rather than for grazing, but its current productivity is slightly higher. This stems from a substantial reduction of productivity (ΔNPP_{LC}) on croplands that can be explained on the one hand by the prevalence of low-yield agriculture in developing countries and on the other hand by the low belowground productivity of crops (25). Table 2 also reveals the low productivity of most of earth's remaining wilderness areas.

Harvest per unit area and year is by far largest on cropland (296 g C/m2/yr), which helps to explain why cropping alone accounts for 50% of global HANPP (Table 2), despite its limited spatial extent (12% of earth's terrestrial surface, excluding Antarctica and Greenland). In total, agriculture (cropping and grazing) is responsible for 78% of global HANPP, the remaining 22% being caused by forestry, infrastructure, and human-induced fires.

A regional breakdown of global HANPP (Table 3) reveals considerably different patterns in various world regions. Aggregate HANPP may be as low as 11–12% in Central Asia, the Russian Federation, and Oceania (including Australia), whereas land is used much more intensively in other regions. For example, Southern Asia has an overall HANPP value of 63%, and land-use intensity is also high in Eastern and Southeastern Europe (52%). Land-use-induced reductions in productivity (ΔNPP_{LC}) vary from 5% in Eastern Asia to 27% in Eastern and Southeastern Europe.

Discussion

The results presented above demonstrate that a remarkable share of global NPP is used to satisfy the needs and wants of just one species on earth, thus indicating the extent of human use of earth's resources. Our HANPP estimate of 15.6 Pg C/yr is slightly higher than the high estimate of Imhoff *et al.* (16) and substantially higher than their intermediate (11.5 Pg C/yr) and low (8.0 Pg C/yr) estimates. Our result is in line with that of Wright (5) and falls well within the range of results given by Vitousek *et al.* (2) according to their different definitions.

Because our results on biomass harvest (NPP_h) involve the extensive use of international databases and cross-checks, we are confident that the global picture portrayed by these data is reliable and rather conservative. In particular, our result on global per capita biomass harvest is lower than that found in several studies of biomass consumption in agrarian and industrialized societies (26). Moreover, we assume a low figure for wood harvest (SI Table 5). Results on land-use-induced productivity changes (ΔNPP_{LC}) may be less robust because of the limited availability of consistent data sources but are within the range of other estimates. Our ΔNPP_{LC} value is lower than the estimate of Vitousek *et al.* (2) but higher than that derived by DeFries *et al.* (10, 27). The latter study, however, might have overestimated the underground fraction of NPP in croplands, which is notably smaller than that of natural vegetation (25). Interestingly, our result for aboveground ΔNPP_{LC} of 5% is almost identical with the figure given by DeFries *et al.* (10) for total ΔNPP_{LC}.

The similarity of our results with those of other authors, however, is partly coincidental, because their definitions of HANPP differ substantially. To evaluate the importance of definitional issues (Table 4), we present a recalculation of HANPP according to the definitions used by Vitousek *et al.* (2) based on our spatially explicit database (column 2) and compare the result with their original data (column 1). The three approaches presented by Vitousek *et al.* depart from the definition we used in our assessment. In their "low estimate," they included only biomass consumed by humans or livestock. Their "intermediate

Table 3. Regional breakdown of global HANPP (excluding human-induced fires) in the year 2000

Region	Area, million km²	NPP_0, gC/m²/yr	NPP_{act}, gC/m²/yr	NPP_h,* gC/m²/yr	NPP_t, gC/m²/yr	HANPP,* %	ΔNPP_{LC}, %
Northern Africa and Western Asia	10.3	83	70	22	48	42	16
Sub-Saharan Africa	24.0	562	497	39	458	18	12
Central Asia and Russian Federation	20.5	405	372	14	358	12	8
Eastern Asia	11.5	363	344	107	237	35	5
Southern Asia	6.7	382	325	183	142	63	15
Southeastern Asia	4.5	1,022	850	133	717	30	17
Northern America	18.5	432	399	62	337	22	8
Latin America and the Caribbean	20.3	811	751	66	685	16	7
Western Europe	3.7	551	512	183	329	40	7
Eastern and Southeastern Europe	2.2	597	436	150	286	52	27
Oceania and Australia	8.4	455	430	25	404	11	6
Total	130.4	502	454	63	391	22	10

For definition of regions, see SI Table 6.

*Excluding human-induced fires.

Table 4. Comparison of global HANPP according to Vitousek *et al.* with a recalculation of HANPP according to definitions provided by Vitousek *et al.* based on our database

NPP-related carbon flows	Definition/ “estimate”	Original Vitousek *et al.* (2) data, Pg C/yr	Our recalculation, Pg C/yr	Deviation, %
NPP$_0$	—	74.80	65.51	+14
NPP$_{act}$	—	66.05	59.22	+12
Food	Low	0.40	0.92	−57
Fodder	Low	1.10	3.25	−66
Wood	Low	1.10	0.97	+14
Total	Low	2.60	5.14	−49
Total as percentage of NPP$_0$	Low	3	8	
NPP of croplands	Intermediate	7.50	6.05	+24
NPP of human-controlled grasslands	Intermediate	4.90	6.65	−26
Consumed on natural grazing land	Intermediate	0.40	1.17	−66
Human-induced fires	Intermediate	3.55	1.14	+212
Wood harvest	Intermediate	1.10	0.97	+14
Wood-harvest losses	Intermediate	0.65	0.33	+97
Land clearing	Intermediate	1.20	Not considered	Undefined
NPP of forest plantations	Intermediate	0.80	1.35	−41
NPP of urban areas	Intermediate	0.20	0.30	−33
Total	Intermediate	20.30	17.96	+13
Total as percentage of NPP$_0$	Intermediate	27	27	
Previous terrestrial total	High	20.30	17.96	+13
Land-use-induced productivity change (ΔNPP$_{LC}$)	High	8.75	6.29	+39
Total	High	29.05	24.25	+20
Total as percentage of NPP$_0$	High	39	37	

estimate” encompassed the total NPP of “human-dominated” ecosystems, and the “high estimate” additionally considered productivity losses compared with potential vegetation (i.e., ΔNPP$_{LC}$). Surprisingly, differences in aggregate results between our recalculation and Vitousek’s original data are relatively small, except for the “low estimate,” which is considerably lower than our recalculation. Here, Vitousek *et al.* used extrapolations of total food and feed use from per capita values for intake of humans and animals, whereas our estimate is based on agricultural statistics. Another part of the difference can be explained by the fact that the calculation made by Vitousek *et al.* referred to data for the late 1970s and early 1980s, whereas our database refers to the year 2000.

Our recalculation gave lower results for appropriated amounts of biomass according to Vitousek’s “intermediate” and “high” definitions, but our results for NPP$_0$ and NPP$_{act}$ were also lower, so that results for HANPP expressed as a percentage of NPP$_0$ are almost identical. We conclude that differences between our results and those of Vitousek *et al.* largely stem from divergences in definitions. Similar considerations apply for other studies. For example, Imhoff *et al.* (16) used still another definition because neither land-use-induced productivity changes nor the NPP on human-controlled areas were assumed to be appropriated. Thus, the similarity of our results with those of Imhoff *et al.* is, to some extent, coincidental. We presume, therefore, that success in harmonizing HANPP definitions would largely eliminate the impression that HANPP calculations are extremely uncertain (17): outcome differences due to different definitions appear to be much larger than those that result from different calculation methods or data.

A large degree of variation exists in the geographical distribution of human use of the biosphere (Fig. 1). The spatial distribution of HANPP expressed as the percentage of NPP$_0$ appropriated in each grid cell (Fig. 1*b*) is a useful indicator of land-use intensity that can quantify and localize changes in ecosystem processes due to human activities. The map presented here differs from that presented by Imhoff *et al.* (16). Their map displays the amount of HANPP resulting from the consumption of humans living in each grid cell, thus attributing HANPP to the place of biomass consumption and not to the locality of appropriation. Our map, instead, localizes the appropriation of NPP and thus the intensity of human domination of ecosystems. Because species richness has been shown to depend on HANPP (5–8), the map presented in Fig. 1*b* contains information crucial for the analysis of biodiversity loss.

Productivity losses compared with the potential vegetation (positive ΔNPP$_{LC}$ values; see Fig. 1*a*) indicate that humans fail to fully use the productive potential of a region. The ratio of harvest to total HANPP can therefore be seen as an indicator of area efficiency: if ΔNPP$_{LC}$ were zero, no productivity would be lost and HANPP would only result from harvest. The regional breakdown presented in Table 3 (for definition of regions, see SI Table 6) supports the view that the marked regional patterns of HANPP result from both variations in natural productivity and predominant land-use systems. For example, in Western Europe, the high total HANPP of 40% coincides with only a small ΔNPP$_{LC}$ because of its high-yielding, intensive agricultural systems. By contrast, in Eastern and Southeastern Europe, with similar ecological conditions, land use has caused a large ΔNPP$_{LC}$ and harvests are low. In Central Asia and the Russian Federation, most HANPP is actually due to a reduction in productivity; the situation is similar in sub-Saharan Africa. The situation in Eastern Asia (including China, Japan, and Korea), in contrast, is characterized by negligible ΔNPP$_{LC}$ but large total HANPP. These findings suggest that, on a global scale, there may be a considerable potential to raise agricultural output without necessarily increasing HANPP, because the industrialized countries were actually able to achieve through agricultural intensification in the last 100–200 years (22).

Our findings emphasize land use as a pervasive factor of global importance. Land use not only transforms earth’s terrestrial surface (28, 29) but also results in changes in biogeochemical cycles (1) and in a deterioration of the ability of ecosystems to deliver services critical to human well being (14). Because human population numbers (30) and per capita consumption of food

(31), fibers, shelter, and maybe also biomass-derived energy (32) are bound to increase over the next decades, cropland areas and the intensity of land use should be expected to rise as well (29, 33). This need not equally raise HANPP, because substantial increases in harvests can be achieved without raising HANPP through intensification (22). Agricultural intensification, however, often incurs other environmental costs, such as surging freshwater and fossil fuel inputs, soil degradation, nitrogen leaching, and pesticide use (29, 33, 34). Some scenarios, nevertheless, predict that cropland area will continue to grow in the next decades to satisfy the needs and wants of a growing world population (33), implying increasing HANPP.

In the light of these results, measures to promote the use of biomass for energy provision as an option to reduce fossil-fuel-related carbon emissions (32, 35) need to be considered carefully. According to our results, humans today already harvest over 8 Pg C/yr. This biomass amounts to an approximate gross calorific value of ≈300 exajoules (EJ) per year, of which some 35–55 EJ/yr are used for the provision of energy services (35). Prominent studies suggest that the use of biomass for energy generation could grow to 200–300 EJ/yr in the next decades (32, 35). The additional harvest of 4–7 Pg C/yr needed to achieve this level of bioenergy use would almost double the present biomass harvest and generate substantial additional pressure on ecosystems. Examples like this demonstrate the complexity of forging strategies of sustainable development and the need for sustainability science (36) to be based on sound empirical analyses of earth's socioecological metabolism.

Methods

We calculated HANPP as the difference between NPP_0 and NPP_t, where NPP_t was calculated by subtracting NPP_h from NPP_{act} (5, 6); that is, our HANPP calculation requires assessments of three parameters: NPP_0, NPP_{act}, and NPP_h. To derive NPP_0, we used the LPJ DGVM (19) with an improved representation of hydrology (18), on the basis of atmospheric CO_2 concentration, gridded data on historical monthly climate, and a soil-type classification at 0.5° spatial resolution as input data (19). After a 900-yr run of spinup to reach equilibrium, repeatedly using the environmental data of the first 30 yr of the 20th century, LPJ was then run for the period 1901–2002. For the HANPP calculation, the 5-yr average of the results from 1998 to 2002 was used and resampled to a resolution of 5 arc min. Aboveground and belowground compartments were separated by using factors dependent on plant functional types and biomes (25). The map of NPP_0 is presented in SI Fig. 2.

For the quantification of NPP_{act} and NPP_h, we combined statistical data (37) on livestock, agricultural yields, and wood harvest at the country level with spatially explicit data on land use in grid-based geographical information systems. A global 5-arc min (≈10 × 10 km) land-use data set that distinguishes five land-use classes (infrastructure/urban, cropland, grazing land, forestry, and wilderness) was derived from recalculations and intersections of the Global Land Cover (GLC) 2000 data (www-gvm.jrc.it/glc2000), a cropland map (38), Forest Resources Assessment/Temperate and Boreal Forest Resources Assessment (FRA/TBFRA) data on forest area (39, 40), and a wilderness map (28). For the 161 countries considered here (97.4% of global land area excluding Greenland and Antarctica), cropland area was consistent with cropland areas reported by the FAO, and forest area was consistent with data form the FRA and TBFRA, which is a precondition for deriving reliable country-level estimates of HANPP in accordance with statistical data on biomass harvest. Rural settlement area was calculated on the basis of model assumptions about per capita area demand, population density, and development status and calibrated against land-use statistics, whereas urban settlement area was taken from the GLC2000 map (www-gvm.jrc.it/glc2000). An existing wilderness map (28) and an NPP threshold of 20 g C/m^2 (41) derived from LPJ-DGVM runs were used to identify areas without land use. Grazing land was then calculated as the difference between the total area of each grid cell and the sum of the previous four classes, assuming that this type of land use occurs in almost all ecosystems (42–44). This data set is complemented by a map of four grazing land quality classes that was derived from land-cover information and LPJ runs. Highly productive ecosystems well suited for grazing (e.g., artificial grassland on fertile soils) were subsumed in class 1, and unproductive, barely suitable ecosystems, such as deserts, semideserts, and shrublands, are in class 4.

The NPP of the actual vegetation was calculated by combining statistical data with LPJ model runs. On cropland, NPP_{act} is defined as the sum of harvested NPP, as reported in statistics and other fractions not accounted for in agricultural statistics, i.e., aboveground crop residues (e.g., straw, stover), NPP losses during the growth period, losses resulting from herbivory, the NPP of weeds, and belowground NPP. Appropriate factors were used to extrapolate flows not reported in agricultural statistics from harvest data (see *SI Text* and Table 7). The spatial allocation of NPP_{act} on cropland to the 5′ cropland grid cells is based on a national productivity index calculated with LPJ, taking irrigation (www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index.stm, 08/2005) into account (see *SI Text*). NPP_{act} of grazing land was calculated on the basis of LPJ runs that were modified to consider the effects of ecosystem and soil degradation, irrigation, and fertilization. An appropriate factor was derived from measured site data to estimate the reduction of productivity resulting from the conversion of forests to artificial grasslands. Soil degradation is considered on the basis of Global Assessment of Human-Induced Soil Degradation (GLASOD) data (45). The supply of biomass available for grazing was cross-checked against the grazing demand of livestock (see *SI Text*). NPP_{act} on infrastructure areas was modeled with LPJ based on assumptions about vegetation cover, productivity, and irrigation (see *SI Text*). NPP_{act} in forests is assumed to be equal to NPP_0 because reliable data are missing to take the effects of forest management on forest productivity into account. NPP_{act} on unused areas is also assumed to be equal to NPP_0.

We defined NPP_h as all biomass harvested or destroyed during harvest within 1 yr. Calculations of NPP_h were based on statistical data on wood and crop harvest (37, 40) and were calculated as 3- to 5-yr averages centered on the year 2000 to reduce the impact of stochastic events, such as unusually good or bad harvests. Biomass harvest on cropland and permanent cultures was derived from the FAO agricultural production database by using factors to extrapolate biomass fractions not reported in statistics discussed in the *SI Text* (see also SI Table 7). Harvest of forestry products was calculated by using the TBFRA2000 database (40) for 52 temperate and boreal countries and FAO statistics (37) for all other countries. Factors used to extrapolate biomass fractions not reported in these statistics (e.g., bark, roots, or leaves) were derived from the TBFRA2000 database and ref. 46 (see *SI Text* and Table 8). The amount of biomass consumed by ruminants on grazing land is assessed on the basis of country-level feed balances, which estimate the demand for grazing as the difference between supply of commercial feed and fodder crops (reported in FAO statistics) and the aggregate demand of livestock. Feed demand was calculated separately for 11 livestock species for which country-specific data on stock and production are provided by the FAO (see *SI Text* and Table 9). Grazed biomass was calculated as the difference between feed demand and the supply of market feed, nonmarket feed from cropland, and feed from crop residues. Grazed biomass is allocated to the grazing land layer on the basis of the grazing land quality map described above, assuming that all quality classes are grazed. Grazing intensity was assumed to be highest in the best-suited grazing areas and lowest in the least suitable ones (see *SI Text*). In contrast to cropland and forestry, no belowground NPP_h was assumed to occur on grazing land because plant roots are mostly not killed during mowing or grazing (4).

Human-induced fires are not included in the spatially explicit assessment but are part of the aggregate estimate of global HANPP summarized in Table 1. They are assessed on the basis of data reported by the FAO and the Global Burned Area 2000 Project. On-site backflow to nature, i.e., unused crop residues, roots or other harvest losses on cropland and in forestry, and livestock feces dropped during grazing were calculated assuming appropriate factors (see *SI Text*).

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1. Crutzen PJ, Steffen W (2003) *Clim Change* 61:251–257.
2. Vitousek PM, Ehrlich PR, Ehrlich AH, Matson PA (1986) *BioScience* 36:363–373.
3. Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) *Science* 277:494–499.
4. O'Neill DW, Tyedmers PH, Beazley KF (2006) *Reg Environ Change* 7:1–14.
5. Wright DH (1990) *Ambio* 19:189–194.
6. Haberl H (1997) *Ambio* 26:143–146.
7. Haberl H, Schulz NB, Plutzar C, Erb K-H, Krausmann F, Loibl W, Moser D, Sauberer N, Weisz H, Zechmeister HG, Zulka P (2004) *Agric Ecosyst Environ* 102:213–218.
8. Haberl H, Plutzar C, Erb K-H, Gaube V, Pollheimer M, Schulz NB (2005) *Agric Ecosyst Environ* 110:119–131.
9. Gerten D, Hoff H, Bondeau A, Lucht W, Smith P, Zaehle S (2005) *Phys Chem Earth* 30:334–338.
10. DeFries RS, Field CB, Fung I, Collatz GJ, Bounoua L (1999) *Global Biogeochem Cycles* 13:803–815.
11. McGuire AD, Sitch S, Clein JS, Dargaville R, Esser G, Foley JA, Heimann M, Joos F, Kaplan J, Kicklighter DW, *et al.* (2001) *Global Biogeochem Cycles* 15:183–206.
12. Field CB (2001) *Science* 294:2490–2491.
13. Daily GC, Alexander S, Ehrlich PR, Goulder L, Lubchenco J, Matson PA, Mooney HA, Postel SL, Schneider SH, Tilman D, Woodwell GM (1997) *Issues Ecol* 1:1–18.
14. Millenium Ecosystem Assessment (2005) *Ecosystems and Human Well Being, Synthesis* (Island, Washington, DC).
15. Wackernagel M, Schulz NB, Deumling D, Linares AC, Jenkins M, Kapos V, Monfreda C, Loh J, Myers N, Norgaard RB, Randers J (2002) *Proc Natl Acad Sci USA* 99:9266–9271.
16. Imhoff ML, Bounoua L, Ricketts T, Loucks C, Harriss R, Lawrence WT (2004) *Nature* 429:870–873.
17. Rojstaczer S, Sterling SM, Moore N (2001) *Science* 294:2549–2552.
18. Gerten D, Schaphoff S, Haberland U, Lucht W, Sitch S (2004) *J Hydrol* 286:249–270.
19. Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kamplan JO, Levis S, Lucht W, Sykes MT, Thonicke K, Venevsky S (2003) *Global Change Biol* 9:161–185.
20. Haberl H, Erb K-H, Krausmann F, Lucht W (2004) *LUCC Newslett* 10:16–17.
21. Haberl H, Krausmann F, Erb K-H, Schulz NB, Rojstaczer S, Sterling SM, Moore N (2002) *Science* 296:1968–1969.
22. Krausmann F (2001) *Land Use Policy* 18:17–26.
23. Haberl H, Erb K-H, Krausmann F, Loibl W, Schulz NB, Weisz H (2001) *Global Biogeochem Cycles* 15:929–942.
24. Davidson C (2000) *BioScience* 50:433–440.
25. Roy J, Saugier B, Mooney HA (2001) *Terrestrial Global Productivity* (Academic, San Diego).
26. Haberl H, Weisz H, Amann C, Bondeau A, Eisenmenger N, Erb K-H, Fischer-Kowalski M, Krausmann F (2006) *J Ind Ecol* 10:151–171.
27. DeFries R (2002) *Geophys Res Lett* 29:1132–1135.
28. Sanderson E, Jaiteh M, Levy M, Redford K, Wannebo A, Woolmer G (2002) *BioScience* 52:891–904.
29. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, *et al.* (2005) *Science* 309:570–574.
30. Lutz W, Sanderson WC, Scherbov S (2004) *The End of World Population Growth in the 21st Century: New Challenges for Human Capital Formation and Sustainable Development* (Earthscan, London).
31. Food and Agriculture Organization (2003) *World Agriculture: Towards 2015/2030, an FAO perspective* (Earthscan, London).
32. Nakicenovic N, Swart R (2000) *Special Report on Emission Scenarios* (Intergovernmental Panel on Climate Change and Cambridge Univ Press, Cambridge, UK).
33. Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D, Swackhamer D (2001) *Science* 292:281–284.
34. Pimentel D, Dazhong W, Giampietro M (1990) in *Agroecology, Researching the Ecological Basis for Sustainable Agriculture*, ed Gliessman SR (Springer, New York), pp 305–321.
35. Goldemberg J (2000) *World Energy Assessment, Energy and the Challenge of Sustainability* (World Energy Council, New York).
36. Kates RW, Clark WC, Corell R, Hall JM, Jaeger CC, Lowe I, McCarthy JJ, Schellnhuber HJ, Bolin B, Dickson NM, *et al.* (2001) *Science* 292:641–642.
37. Food and Agriculture Organization (2004) *FAOSTAT 2004, FAO Statistical Databases: Agriculture, Fisheries, Forestry, Nutrition* (Food and Agriculture Organization, Rome).
38. Ramankutty N, Foley JA (1998) *Global Biogeochem Cycles* 12:667–685.
39. Food and Agriculture Organization (2001) *Global For Resour Assess 2000* (Food and Agriculture Organization, Rome).
40. United Nations (2000) *Forest Resources of Europe CIS, North America, Australia, Japan, and New Zealand (industrialized temperate/boreal countries), UN-ECE/FAO Contribution to the Global Forest Resources Assessment 2000, Main Report ECE/TIM/SP/17* (United Nations, New York).
41. Lamprey HF (1983) in *Tropical Savannas, Ecosystems of the World 13*, ed Bourliere F (Elsevier, Amsterdam), pp 643–666.
42. Lambin EF, Turner BLI, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C (2001) *Global Environ Change* 11:261–269.
43. Conant RT (2002) *Grazer-Dominated Ecosystems* (Macmillan, London).
44. Asner GP, Elmore AJ, Olander LP, Martin RE, Harris AT (2004) *Annu Rev Environ Res* 29:261–299.
45. Oldeman LR, Hakkeling RTA, Sombroek WG (1990) *World Map of the Status of Human-Induced Soil Degradation* (International Soil Reference and Information Centre/United Nations Environment Programme, Wageningen, The Netherlands).
46. Pulkki RE (1997) *Literature Synthesis on Logging Impacts in Moist Tropical Forests*, Global Fibre Supply Study Working Paper Series, eds Duinker PN, Bull G (Food and Agriculture Organization, Rome). Available at ftp://ftp.fao.org/docrep/fao/006/W8270E/W8270e.pdf. Accessed June 25, 2007.