Global human appropriation of net primary production doubled in the 20th century

Supporting Information

Fridolin Krausmann,[1,*] Karl-Heinz Erb,[1] Simone Gingrich,[1] Helmut Haberl,[1] Alberte Bondeau,[2,3] Veronika Gaube,[1] Christian Lauk,[1] Christoph Plutzar,[1]Timothy D. Searchinger[4]

[1] Institute of Social Ecology Vienna (SEC), Alpen-Adria University, Schottenfeldgasse 29, A-1070 Vienna, Austria

[2] Mediterranean Institute of Biodiversity and Ecology (IMBE), Aix-Marseille University - CNRS - IRD - UAPV, F-13545 Aix-en-Provence cedex 04, France.

[3] Potsdam Institute of Climate Impact Research, P.O. Box 60 12 03, D-14412 Potsdam, Germany.

[4] Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544

*Corresponding author, fridolin.krausmann@aau.at

http://www.uni-klu.ac.at/socec/eng/inhalt/1090.htm

1 SI methods and data sources:

We base our estimate of human appropriation of net primary production (HANPP) on the concept and definition of HANPP explained in previous work (1,2). HANPP can be expressed as

$$HANPP = NPP_{pot} - NPP_{eco} = HANPP_{luc} + HANPP_{harv}$$

NPP_{pot} is defined as the NPP of potential vegetation, i.e. the vegetation assumed to exist without land use under current climate (3). NPP_{eco} is the NPP remaining in ecosystems after harvest. NPP_{eco} is calculated by subtracting $HANPP_{harv}$ from the NPP of the currently prevailing vegetation (NPP_{act}) (1, 4, 5).

As far as possible, we followed the methodology outlined in our previous work to estimate HANPP and its components, which were developed to quantify HANPP for the year 2000. Where necessary we adapted the methodology and estimation procedures for application to historical time periods. In particular, we adjusted the procedures to estimate harvest flows not covered in statistical sources and methods to estimate $HANPP_{luc}$. Results of HANPP parameters for the year 2000 are reasonably consistent with those presented in our previous study for the year 2000 (1); minor differences are mainly due to differences in NPP_{pot} resulting from improvements of the Lund Potsdam Jena managed Lands (LPJmL) dynamic global vegetation and water balance model.

1.1 Temporal and spatial resolution of the HANPP database:

We calculated HANPP for nine points in time: 1910, 1930, 1950, 1961, 1970, 1980, 1990, 2000 and 2005 for individual countries or world regions. For the period 1961 to 2005 the HANPP database distinguishes between 161 individual countries covering 97.4% of the global land area and 99.9% of the global population. Due to data restrictions we calculated HANPP for 11 world regions for the years 1910, 1930 and 1950. For a list of countries and world regions see section 1.5. HANPP flows were calculated as three-year averages to reduce the impact of annual weather fluctuation on HANPP results. At the global scale for the period 1961 to 2005 we also calculated a time series in annual resolution, as most input data were available at an annual basis. Where annual input data were not available, we interpolated data and coefficients.

1.2 NPP of the potential vegetation (NPP_{pot}):

NPP_{pot} was derived from model runs of the LPJmL global vegetation model (6) with an improved representation of hydrology (7). LPJmL is a biogeochemical process model of climate-dependent carbon and water dynamics in vegetation growth. Model inputs are atmospheric CO_2 concentration, gridded data on historical monthly climate, and a soil type classification at 0.5° spatial resolution (6). In order to allow carbon pools and fluxes to reach equilibrium, LPJmL was run for 900 years of spinup. NPP_{pot} is calculated on an annual basis between 1908 and 2006. The annual NPP_{pot} results were used to calculate five-year averages for each point in time. For 2005, the four-year average (2003 – 2006) was computed.

Negative NPP_{pot} values (occurring in gridcells in single years when relatively humid, precipitation-rich years are followed by severe aridity and the large respiration exceeds gross primary production) were set to nil. NPP_{pot} on cropland was calculated on basis of the History Database of the Global Environment (HYDE) cropland time series (8) intersected with the NPP_{pot} calculation. As HYDE 3.1. ends in the year 2000, the calculation of NPP_{pot} on cropland was based on the cropland layer for 2000 and the four-year average of NPP_{pot} for 2005. The development of NPP_{pot} in the period 1910-2005 can be seen in Figure S2

CO_2 fertilization effect: LPJmL results show a considerable increase in net primary production (NPP) over the last century, mainly due to the so called CO_2 fertilization effect. Many uncertainties, however, relate to this effect: In free air carbon dioxide enrichment (FACE) experiments, strong effects of NPP increase (in particular forests or coppice (9) have been found (+20%)). Two mechanisms are responsible for this effect: (a) enhanced carbon assimilation rates due to elevated partial carbon pressure although the magnitude of the response varies widely in dependency of environmental constraints and phenological characteristics, (b) improved water-use efficiency as many plants use water more efficiently under elevated CO_2 concentrations due to reduced stomatal conductance and leaf transpiration. However, large uncertainties prevail, which prevent straightforward predictions of vegetation responses to elevated CO_2 in the current state of knowledge. These knowledge gaps relate to the allocation of carbon to various carbon pools with different turnover times, and to the impact of essential variables, such as nutrient availability, which have been found to be decisive for plant responses to elevated CO_2 (10-12). In general fertilization by CO_2 (and also N) is expected to saturate at high levels (13). Additionally, there is evidence that crops grown under elevated CO_2 concentrations might be more susceptible to insect pests. The same caveats, of course, relate to the backcasting procedure followed in our studies, and calls for caution when interpreting the trajectory of NPP_{pot} (see also sensitivity analysis in section 1.5 below).

1.3 Harvested NPP ($HANPP_{harv,}$ harvest):

Items: $HANPP_{harv}$ comprises used and unused biomass extraction. Used extraction denotes all biomass extracted for further socioeconomic use and includes harvested crops, used crop residues, forage, fuelwood and industrial roundwood as well as biomass grazed by livestock. This fraction is consistent with biomass flows accounted for under the item ‘domestic extraction’ in material flow accounting (14,15). Unused biomass extraction denotes all above- and belowground biomass compartments killed during harvest, i.e. roots on cropland and forests. Biomass killed in human induced vegetation fires resulting from deforestation and swidden agriculture is also subsumed under $HANPP_{harv}$. According to our calculation only between 56 and 63% of total global $HANPP_{harv}$ are actually used.

Temporal resolution and extrapolation: We calculated three-year averages of biomass harvest after 1960, in order to avoid fluctuations due to annual weather variations. For 1910, 1930 and 1950 data restrictions did not allow to compute three year averages. $HANPP_{harv}$ was converted into tons of carbon (tC) by assuming an average carbon content of dry matter (DM) biomass of 50%.

For the years 1961 to 2005, a period with available data from the database of the Food and Agricultural Organization of the United Nations (FAO), biomass harvest was calculated for 161 individual countries or regions covering 97.4% of the global land area and 99.9% of the global population. For the years 1910, 1930 and 1950 data coverage in statistical sources was incomplete. Countries/regions comprised in the statistical yearbooks of FAO (16) and the Institut International d'Agriculture (IIA) (17-19) cover only a fraction of the global population and land area. At the global scale coverage in 1910 and 1930 was between 61% and 68% of global total population and land area, with considerable variations across regions. It covered between 75% and 85% of population in most regions, was above 95% for Western Europe and Northern America and was particularly poor (10-30%) for Eastern Asia and Subsaharan Africa. The 1950 dataset was more complete, covering 95% of world population and 91% of the land area. To arrive at a total harvest account for each of the 11 world regions, we used the national data available in each region to extrapolate to the regional totals on the basis of per capita values and population numbers (20).

Crop harvest: Biomass harvest from cropland and permanent cultures was calculated from FAO agricultural production database (21, 22), statistical yearbooks of FAO and its precursor organization (16-19). Data reported in fresh or air dry weight were converted into dry matter using crop specific data on moisture content according to standard tables of food and feed composition (23-26).

Used and unused aboveground harvest residues from cropland harvest were extrapolated from the amount of primary product harvest using specific harvest factors for 17 crop groups in eight different world regions. For the year 2000 and 2005 we used the harvest factors available from ref. (1) (Table M1). In order to take improvements in harvest indices of major cultivars into account, we modified harvest indices over time. Based on information on the development of harvest indices in the 20^{th} century for selected cultivars derived from a literature review (e.g., 27-30) we assumed that harvest factors in 1910 were between 5% (South and Central Asia) and 32% (Western Europe) above those given in ref. (1) for the year 2000. Table M2 presents the regional multipliers used to extrapolate harvest factors for historic points in time from the harvest factors given in ref. (1). To distinguish between recovered and not recovered fractions of aboveground residues we used the set of region specific factors (31) (Table M1b).

All belowground NPP on cropland is assumed to be killed during harvest and is accounted for as $HANPP_{harv}$. Belowground residues on cropland were extrapolated from aboveground extraction by using the ratio of aboveground and belowground NPP (32) (Table M1c).

Table M1. Harvest factors, recovery rates, and above/belowground ratios used to extrapolate $HANPP_{harv}$ from agricultural statistics for the year 2000 from ref. (1). The mass of crop residues is calculated with crop-specific and region-specific information on harvest indices taken from the literature (27, 31, 33). The derived harvest factors distinguish between 17 groups of crops and 8 world regions (a). Recovery rates (b) are used to distinguish between harvested/recovered and unused residues on the basis of region and crop specific recovery rates (31). Belowground NPP, i.e. NPP allocated to roots, tubers etc., is calculated using the ratio of belowground to aboveground NPP taken from ref. (32). Regional aggregation according to ref. (1)

	E. Asia	E. Europe	Latin America	N. Africa W. Asia	N. America Oceania	S. and C. Asia	Subsahara n Africa	W. Europe
a) Harvest factors. Crop residue [g dry matter (DM) per year] = primary crop harvest [g DM/yr] * harvest factor.								
Wheat, other cereals	1.5	1.5	1.5	1.5	1.2	1.7	2.3	1.0
Rice, Paddy	1.0	1.2	1.2	1.2	1.2	1.5	1.5	1.2
Maize	3.0	1.9	3.0	3.0	1.2	3.5	3.5	1.2
Millet	3.0	1.9	3.0	3.0	1.2	3.5	3.5	1.2
Sorghum	3.0	1.9	3.0	3.0	1.2	3.5	3.5	1.2
Roots and Tubers	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Cassava	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Sugar Cane	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Sugar Beets	0.7	0.5	0.7	0.7	0.5	0.7	0.7	0.5
Pulses	0.4	1.0	0.4	0.4	1.0	0.4	0.4	1.0
Soybeans	1.2	1.5	1.5	1.5	1.2	1.5	1.5	1.2
Groundnuts in Shell	1.2	1.2	1.5	1.5	1.2	1.5	1.5	1.2
Oil Palm Fruit	1.5	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Castor Beans	0.4	1.0	0.4	0.4	1.0	0.4	0.4	1.0
Rapeseed, oil crops	2.3	1.9	2.3	2.3	1.9	2.3	2.3	1.9
Fodder crops	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Permanent crops	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
b) Recovery rates: Used crop residues [g DM] = available residues [g DM] * recovery rate.								
Cereals	0.8	0.75	0.8	0.8	0.7	0.9	0.9	0.7
Roots and Tubers	0.75	0.25	0.75	0.75	0	0.75	0.75	0
Sugar Cane	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Sugar Beets	0.75	0.25	0.75	0.75	0	0.75	0.75	0
Sugar Crops nes	0.8	0.3	0.8	0.8	0	0.8	0.8	0
Beans, Dry	0.5	0.5	0.5	0.5	0	0.5	0.5	0
Other pulses	0.8	0.75	0.8	0.8	0.7	0.9	0.9	0.7
Other oil crops	0.8	0.75	0.8	0.8	0.7	0.9	0.9	0.7
Oil Palm Fruit	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Sunflower Seed	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Rape seed	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7

c) Belowground/aboveground NPP ratios and loss factors for the calculation of NPP_{act} on cropland from $HANPP_{harv}$

	Least developed countries	Developing countries	Transition markets	Industrialized countries
Belowground NPP/aboveground NPP	0.15	0.15	0.15	0.15

Table M2: In order to take changes in harvest indices (corn to straw ratios) over time into account we used multipliers to adjust harvest factors given in Table M1. Time specific harvest factors were derived from multiplying harvest factors for the year 2000 given in Table M1a with the region specific multiplier given below. Regional aggregation according to ref. (1)

	South & Central Asia	East Europe	North Africa & West Asia	North America & Oceania	West Europe	Sub-Saharan Africa	Latin America & Caribbean	East Asia
1910	1.05	1.10	1.10	1.20	1.32	1.05	1.10	1.10
1930	1.05	1.10	1.10	1.20	1.31	1.05	1.10	1.10
1950	1.05	1.10	1.10	1.19	1.30	1.05	1.10	1.10
1962	1.05	1.10	1.10	1.17	1.27	1.05	1.10	1.10
1970	1.05	1.09	1.09	1.13	1.20	1.05	1.09	1.09
1980	1.04	1.07	1.07	1.08	1.10	1.04	1.07	1.07
1990	1.03	1.04	1.04	1.03	1.03	1.03	1.04	1.04
2000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Grazed biomass: Data on the amount of roughage grazed by livestock is not available from statistical sources. In order to compute the amount of biomass consumed by ruminants either directly through grazing or indirectly through harvest of hay or silage we established feed balances for each country or region (years 1910, 1930, 1950) (1,34). The demand for roughage was calculated for each country/region as the difference between the total calculated feed requirement of roughage consuming livestock and the total feed available from commercial feed, forage crops and crop residues used as feed and aggregate feed. This method does not allow distinguishing between grazed biomass and grass harvested for silage or hay production. Country-specific data on livestock, supply of commercial feed and fodder crops as well as animal production is available from FAO (16) and the IIA (17-19). Data on commercial feed supply and animal production was only available for the period 1961 to 2005.

Daily feed demand of cattle and buffalo was estimated on the basis of linear correlations between average daily feed intake per head of the national stock and average national milk yield and carcass weight (1, 34). Table M3 provides an overview of the resulting calculated average daily dry matter intake rates for cattle and buffalo by world regions.

Table M3: Calculated feed intake of cattle and buffalo in [kg DM/head/day]. Averages for world regions. Regional aggregation according to ref. (1).

	South & Central Asia	**East Europe**	**North Africa & West Asia**	**North America & Oceania**	**West Europe**	**Sub-Saharan Africa**	**Latin America & Caribbean**	**East Asia**	**World**
1962	5.8	7.5	6.9	9.7	9.5	6.8	8.5	6.4	7.6
1970	5.9	8.0	7.2	11.0	10.3	6.9	8.6	6.7	8.0
1980	6.0	8.5	7.4	12.2	11.3	6.9	8.5	7.2	8.4
1990	6.3	9.3	7.2	14.0	12.6	6.8	8.7	7.6	8.7
2000	6.6	9.2	6.8	14.3	13.9	6.7	9.5	8.0	9.0
2005	6.6	10.4	7.1	14.4	14.5	6.7	9.6	9.0	9.3

Region-specific rates for daily feed intake of other roughage consuming livestock (sheep, goats, horses, asses and mules) were taken from ref. (1). These rates were not modified for historic points in time.

Table M4: Feed demand coefficients for pork, poultry and eggs. Feed requirements to produce pork, poultry and eggs were calculated on the basis of production data of animal products from (21) and conversion factors for the year 2000 given in ref. (1). Improvements of conversion efficiency were taken into account by adjusting the factors applying time and region specific multipliers:

	South & Central Asia	East Europe	North Africa & West Asia	North America & Oceania	West Europe	Sub-Saharan Africa	Latin America & Caribbean	East Asia
a) Conversion factors for pork and time-specific multipliers								
Pig meat conversion factors: feed demand [kg DM]=kg produce [kg fresh weight]* conversion factor								
2000								
Pig meat	8.0	5.0	6.0	4.0	4.0	8.5	9.0	5.0
Efficiency factors: multiplier to arrive at conversion factors for the specific year								
1962	1.10	1.40	1.40	1.30	1.50	1.05	1.00	1.40
1970	1.08	1.20	1.32	1.10	1.20	1.04	1.00	1.20
1980	1.05	1.10	1.21	1.05	1.08	1.03	1.00	1.10
1990	1.03	1.05	1.11	1.02	1.03	1.01	1.00	1.05
2000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2005	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
a) Conversion factors for poultry and eggs and time-specific multipliers								
Poultry conversion factors: feed demand [kg DM]=kg produce [kg fresh weight]* conversion factor								
2000								
Poultry	5,1	4,0	4,4	3,0	3,0	5,5	3,6	4,3
Eggs	3,8	3,0	3,0	2,8	2,8	4,0	3,0	3,0
Efficiency factors: multiplier to arrive at conversion factors for the specific year								
1962	1.05	1.30	1.25	1.40	1.40	1.00	1.30	1.25
1970	1.04	1.24	1.20	1.32	1.32	1.00	1.24	1.20
1980	1.03	1.16	1.13	1.21	1.21	1.00	1.16	1.13
1990	1.01	1.08	1.07	1.11	1.11	1.00	1.08	1.07
2000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2005	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

FAO commodity balances (21, 22) provide data on the total amount of commercial feed available. In order to quantify the amount of feed available for grazers we also estimated the feed demand of pigs and poultry. We assumed that the difference between available market feed according to FAO and dry-matter feed demand of pigs and poultry is used as market feed supply of cattle and other roughage-consuming livestock. Feed demand for pigs and poultry is calculated using region-specific efficiency factors for dry matter feed demand per unit of pork, poultry and egg production. We used the efficiency factors for the year 2000 reported in ref. (1) and made rough modifications to account for improvements in feeding efficiency during the last century based on ref (35). We assumed that efficiency of pork and poultry production improved between 5% (least developed regions, e.g. South and Central Asia) and 50% (industrialized countries, e.g. West Europe) between the year 1960 and 2000 (Table M4). We used data on pork, poultry and egg production from FAO (21, 22) to calculate dry matter feed demand for each country/region.

For the years 1910, 1930 and 1950 we kept the feed demand factors constant at the level of 1960 for all livestock species, assuming that productivity changes occurred predominantly in the second half of the 20th century.

Grazed biomass was calculated as the difference between total feed demand of grazers and the calculated available amount of market feed, forage products from cropland and crop residues used as feed. For the years prior to 1961, for which no data on commercial feed supply was available from statistical sources, we kept the share of the different feed fraction in total supply feed supply constant at the level calculated for each country/region calculated for 1961.

Forest harvest: Harvest of wood is calculated from FAO forestry production database (21, 22) which provides information on fuel wood and industrial roundwood production for the years 1961 to present. Data given in solid cubic meters were converted into tons of carbon by using factors on wood density and carbon content available for 6 different vegetation zones and deciduous and coniferous species derived from (36-38). Data on wood harvest prior to 1960 are scarce and fragmentary. To estimate wood harvest for the years 1910, 1930 and 1950, we used various statistical sources including data provided in an early forestry assessment of FAO (39) and compilations of forestry data (e.g., refs. (40, 41)). Data reported for wood harvest reported in these sources only allow quantifying forest harvest for a time period around 1920 and for 1950. We cross-checked the data, comparing per-capita wood consumption derived from the above-mentioned sources with per-capita harvest reported for 1961 for each country. In cases where per capita harvest amounted to less than 80% of the value of 1961 we raised it to 80%. At the global scale these adjustments increase wood harvest by 20% for 1920 and 10% for 1950, compared to the original sources. Forest harvest for 1910 and 1930 was calculated on the basis of national per capita wood harvest of 1920 and population data of 1910 and 1930. Population data were derived from ref. (20).

Unused above- and belowground residues of wood extraction include felling losses, bark and root biomass of felled trees and were extrapolated from dry matter wood harvest. We used a bark factor (wood underbark as percentage of wood overbark) of 0.9, derived from FAOs forest resource assessment (42), to extrapolate bark harvest. Felling losses were estimated using recovery rates defined as the ratio of wood removals to fellings (42, 43). Belowground losses in forestry, i.e. root biomass killed through wood harvest, was calculated applying root to total factors for forests (32).

Biomass harvest from infrastructure and settlement areas: A considerable fraction of the land used for infrastructure and settlements is covered with vegetation (e.g. gardens, parks, grass strips along roads). This vegetation usually is intensively managed. To account for $HANPP_{harv}$ through gardening or park and infrastructure maintenance we assumed that 50% of the aboveground NPP on these areas (see section below) is harvested.

Biomass killed in human induced fires (deforestation and swidden agriculture): This $HANPP_{harv}$ fraction comprises forest biomass killed for the purpose of land clearing, dominated by human induced fires; it does not include the amount of biomass burned on grasslands (excluded for reasons of data availability). Reference (44) provides data on net deforestation for the period 1850 to 1990 in regional resolution. This data was extrapolated for 2000 and 2005 on basis of the Forest Resource Assessment (45). For Latin America, Subsaharan Africa and South East Asia, we additionally assess the amount of biomass killed due to swidden agriculture, which is not comprised in ref. (44). This biomass flow was assessed by multiplying estimates on the extent of area burnt each year with the average biomass density and a burning efficiency of 54% (46). The extent of area burned each year in swidden agriculture was estimated on basis of assumptions on the fraction of the regional population living in swidden cultivation systems and the per-capita area requirement of this population. The number of people living mainly from swidden agricultural systems in 1950 were derived from ref. (47). For South-East Asia and Sub Saharan Africa we assumed the fraction of swidden to regional population to be constant prior to 1950. For Latin America we assumed a decline from 75% of the total population in 1900 to 48% in 1950. For 2005, a published analysis (48) reports population numbers of swiddeners for South-East Asia. Due to the lack of recent data for other regions, we used a study from 1980 (49), containing area, population and forest type estimates (open/closed) of swidden agriculture for 1980 in order to extrapolate the data provided in ref. (48) to the two other regions, implicitly assuming that the share of population living as swiddeners between the regions did not change over time. Subsequently, the area requirement was calculated as a function of population numbers, per-capita energy demand (assuming that two thirds of a total calorific intake of 4 gigajoule per capita and year (GJ/cap/yr) is derived from swidden agriculture), and agricultural yields. The length of the rotation cycle (fallow periods) was assumed to decrease linearly from 15 years in 1900 to 8 years in 2010 and as an effect of declining fallow periods (50), yields were assumed to decline in parallel linearly from 24 GJ/ha/yr in 1900 to 17 GJ/ha/yr in 2010. The biomass density at the time of slash is derived from ref. (51) for open forests and ref. (52) for closed forests.

1.4 NPP foregone due to land conversion ($HANPP_{luc}$, NPP loss):

$HANPP_{luc}$ represents the difference between the NPP of the vegetation prevailing under actual land uses (NPP_{act}), and the NPP of land if it had remained in its original, native vegetation and unaltered by irrigation, drainage, fertilization and other management practices (NPP_{pot}). In most cases, land use reduces NPP, at least over larger areas, as few croplands achieve the NPP of the native forests or grasslands they replace, and $HANPP_{luc}$ represents this reduction in NPP. In regions where precipitation or nutrient availability limit NPP, irrigation and fertilization can also increase NPP (e.g. industrial agro-ecosystems in The Netherlands or irrigated drylands in Egypt or Pakistan).

Cropland: $HANPP_{luc}$ on cropland was calculated as the difference between the NPP_{act} and NPP_{pot} on cropped area. NPP_{act} on cropped area was extrapolated from $HANPP_{harv}$. As outlined above, $HANPP_{harv}$ on cropland comprises harvested crops as well as all belowground biomass killed during harvest. We assume that NPP_{act} on cropland equals the sum of $HANPP_{harv}$ and pre-harvest losses due to herbivory and weeds. We defined four different levels of pre-harvest losses (Table M5). For each point in time we assigned each country/region to a corresponding level based on development status and fertilizer use per unit of agricultural land as proxies for technology. Least-developed countries were classified as level 1 in all years, developing countries as level 1 from 1950-1970 and level 2 from 1980-2000. Transition markets were considered as level 2 from 1950-1970 and level 3 from 1980-2000, and industrialized countries level 3 from 1950-1970 and level 4 from 1980-2000. This allocation was adjusted on the basis of fertilizer use: Countries were assigned to the next higher level if fertilizer use per area of agricultural land was higher than the values given in Table M5.

Table M5: Loss expansion factors to assess pre harvest losses of NPP on cropland and range of fertilizer use per unit of agricultural land used to adjust the allocation of individual countries to a specific level. Total NPP_{act} including pre harvest losses is calculated as $HANPP_{harv}$ * loss expansion factor.

	Level 1	**Level 2**	**Level 3**	**Level 4**
Loss expansion factor	1.36	1.23	1.18	1.14
Fertilizer use (kg/ha/yr)	< 10	20-50	50-150	> 150

NPP_{act} on fallow areas (calculated as the difference between total cropland and total cropped area) was assumed to be 80% of NPP_{pot} of cropland lying fallow (1). NPP_{pot} on fallow cropland was calculated on basis of the spatially explicit data from the HYDE cropland time series (8) (http://themasites.pbl.nl/en/themasites/hyde/index.html) intersected with the LPJmL time series results for NPP_{pot} and the national fraction of fallow in percentage of overall cropland in each country based on FAO data (21).

Grassland: We assumed that the NPP_{act} of natural, non-degraded grasslands is not affected by low to moderate grazing pressure, as it is impossible to judge whether disturbance effects (e.g. biomass destruction due to trampling) or over-compensatory plant growth induced by grazing and fertilization from manure droppings dominate (53). Furthermore, evidence from Sub-Saharan Africa suggests that livestock introduction to natural grasslands with populations of large-herbivores will decrease the carrying capacity of natural herbivores resulting in unaltered grazing pressure (54). Therefore, we assumed $HANPP_{luc}$ on ”natural grasslands” to be zero in the absence of human-induced soil degradation. This conservative assumption of NPP_{act} being equal to NPP_{pot} does not hold true for artificial grazing lands or on degraded land.

We calculated $HANPP_{luc}$ on grassland for two distinct cases: (a) losses of NPP due to the conversion of forest stand to artificial grasslands. In line with our previous work (1), we assume that the conversion of forests to grassland (human-controlled grasslands) results in a reduction of NPP by 20%. This factor is derived from a comparison of 41 measured site data on NPP of grasslands, located in all major forest biomes of the world (55-59) and LPJ results for the respective grid cells. (b) The amount of NPP lost due to human-induced soil degradation in dry grazing lands. In the absence of better data we assessed this effect on basis of data for the year 2000 (60) which was extrapolated backwards by assuming that the amount of $HANPP_{luc}$ is a stable fraction of $HANPP_{harv}$ from grazing. This approach yielded similar results as an intersection of gridded time series data for pasture areas (8) with the Global Assessment of Human-induced Soil Degradation map (61) and the time-series NPP_{pot} results derived with LPJ. In a previous study (1), we did consider negative $HANPP_{luc}$ values on fertilized pasture land in countries with intensive pasture management and assumed pasture improvement for 17 countries, resulting in a comparatively small reduction of $HANPP_{luc}$ on global grazing land by 3.0% and by 1.2% of total $HANPP_{luc}$ in the year 2000. Due to a lack of data on the historic development of irrigation and fertilization of grasslands it was not possible to take improvements of NPP on pastures into account for the time series presented in this paper, which likely results in a slight overestimation of $HANPP_{luc}$ mostly in the Western Industrial region. Better datasets are vitally required for better understanding this effect of land use on NPP.

Settlement and infrastructure areas: Based on our previous work (1) we assumed that 2/3 of settlement and infrastructure areas are actually covered with built structures and do not bear vegetation cover; on these areas NPP_{act} is assumed to be zero. On the remaining 1/3 of the area, we assumed that NPP_{act} equals NPP_{pot}. The national area-related $HANPP_{luc,}$ measured in [gC/m²/yr] derived from ref. (1) for the year 2000, was applied to an estimate of the development of the national infrastructure and settlement areas from 1910 to 2005. The extent of infrastructure and settlement areas was estimated by combing per capita infrastructure area demand values (a function of population density and development status) derived from ref. (62) and population numbers.

Forest and wilderness areas: Forest management and wood harvest have contrasting effects on NPP which are difficult to assess on the global scale: On the one hand, juvenilization can increase forest NPP, in particular NPP allocated to stemwood growth (63, 64). On the other hand, harvest events eliminate vegetation on fractions of the forests, and thus lower NPP of the overall forest area (65, 66). We therefore assumed that on forest and wilderness areas NPP_{act} equals NPP_{pot}. Hence $HANPP_{luc}$ of these areas is by definition zero.

1.5 Sensitivity analysis

In order to test the robustness of our results we made assumptions on leading uncertainties and calculated a high and low estimate of HANPP. Uncertainties in the HANPP calculation can be related to the used statistical data, to the assumptions underlying the applied estimation procedures and to LPJmL model results. In order to arrive at a high and low estimate of global HANPP shown we made assumptions on the uncertainty range of the most important input data and assumptions. Table M6 shows the percentage values of the applied up- and downward changes of the data and assumptions used in the standard estimate. To test the robustness of our results against changes in NPP_{pot} we also calculated HANPP assuming constant NPP_{pot}, i.e. assuming no effect of CO_2 fertilization and climate change on NPP_{pot}. This is based on the assumption that the LPJmL model results which show a considerable increase in NPP_{pot} between 1910 and 2005 are rather on the high side. For the estimate of HANPP with constant NPP_{pot} we used the global NPP_{pot} value of 1990, as the LPJmL model has been calibrated against field measurements of NPP which mostly stem from this period. Figure 1B in the main text presents the aggregate results for HANPP in PgC/yr and in HANPP as % of NPP_{pot} of the high and low estimates as well as the HANPP calculation with constant NPP_{pot}.

Table M6: Percentage changes of data and assumptions used in the standard HANPP estimate to calculate a high and low estimate of global HANPP. For forest harvest data the uncertainty range is based on an extensive literature review of high and low estimates of timber and fuelwood extraction for individual countries and regions (34). For grazed biomass the low range was derived from alternative grazing estimates (31, 67) which arrive at a lower value for grazed biomass than our standard estimate. All other assumptions are based on an educated guess of the likely uncertainty range.

	1910	2005
High HANPP estimate		
Crop harvest data	+15%	+10%
Pre-harvest losses cropland	-45%	-30%
Forest harvest data	+45%	+30%
Grazing estimate	+15%	+10%
$HANPP_{luc}$ soil erosion	+50%	+20%
$HANPP_{luc}$ artificial grassland	+50%	+50%
Low HANPP estimate		
Crop harvest data	-15%	-10%
Pre-harvest losses cropland	+45%	+30%
Forest harvest data	-17%	-11%
Grazing estimate	-38%	-25%
$HANPP_{luc}$ soil erosion	-50%	-20%
$HANPP_{luc}$ artificial grassland	-50%	-50%

1.6 Scenarios for the development of HANPP until 2050

We calculated five different scenarios for the development of HANPP between 2005 and 2050 based on projections of global economic growth (scenario A), population growth in the five world regions (scenario B), projections of global consumption of biomass products (scenario C) and a low and high boundary level for primary biomass harvest for energy production (scenario D and E).

Scenario A extrapolates HANPP on the basis of the baseline projections according to the Organization for Economic Co-operation and Development's Global Economic Outlook (68), which assumes an annual growth rate of real gross domestic product (GDP) of 2.8% until 2050 (+246% between 2005 and 2050). We assumed that the ratio of HANPP per unit of GDP will further decline by 66% between 2005 and 2050, based on an extrapolation of the trend from 1910 to 2005 fitting an exponential function.

Scenario B extrapolates HANPP on the basis of population forecasts for each of the five world regions. We used population data from the medium variant of the 2010 Revision of the United Nation's (UN) World Population Prospect (69) which predicts an increase in global population between 2005 and 2050 of 43%. We assumed that HANPP per capita in the five world regions will further decline by between 15% and 28%, based on extrapolations of the trend from 1910 to 2005 fitting exponential functions.

Scenario C extrapolates HANPP on the basis of assumptions on the future demand for biomass products (final consumption of biomass). Based on data for final biomass consumption between 1960 and 2005 derived from FAOs commodity balances and forest product statistics (21) we assumed global average final biomass consumption per capita to remain constant at 0.3 tC/cap/yr. We further assumed that average HANPP per unit of final biomass consumption will decline by 26% towards the level currently observed in the Asia region, which has the lowest level of all five world regions. An extrapolation of the trend of the HANPP per unit of final biomass consumption between 1960 and 2005 fitting an exponential function yields a similar result. Total HANPP in 2050 was calculated using population data from the medium variant of the UN's World Population Prospect (69).

The bioenergy scenarios D and E add additional primary bioenergy production to the outcome of the intermediate Scenario B. Based on the deployment potential of terrestrial biomass for bioenergy presented in the special report of the Intergovernmental Panel on Climate Change (70) we assumed a lower and upper boundary value for biomass harvest for bioenergy production of 100 and 300 exajoules per year (EJ/y) in 2050. Considering that around 50 EJ of primary biomass have already been used in energy production in 2005 (71) we assumed additional biomass harvest for energy production to range between 50 EJ/y (Scenario D) and 250 EJ/y (Scenario E) in 2050. The International Energy Agency endorsed goal of producing 20% of the world's energy from bioenergy by 2050 as part of a climate change strategy (72) is well within this range: Using the OECD projection of 900 EJ of primary energy use in 2050 (73) and depending on the inclusion/exclusion of traditional bioenergy and assumptions on the conversion efficiency of bioenergy production roughly 170-210 EJ of primary biomass need to be harvested for bioenergy production in 2050.

We assumed that 60% of the additional bioenergy in Scenario D and E is produced from agricultural biomass and 40% from forest biomass. HANPP associated with the extraction of this additional biomass was calculated by using appropriate coefficients of HANPP per unit of biomass harvest. We assumed that the ratio HANPP per unit of agricultural biomass harvest further declines by 32% based on historical trends fitting an exponential function. No improvements were assumed for forest biomass, where HANPP is calculated as harvest times a constant coefficient for belowground biomass.

In the scenarios we did not assume any further increase in NPP_{pot}, but as the sensitivity analysis (see section 1.5. and Figure 1D in the main text) has shown, the HANPP framework is very robust against changes in $NPP_{pot.}$ and little impact of the assumption of a constant NPP_{pot} (at the value of 1990) on the scenario results.

1.7 World Regions: Definition of regions used in our calculation. The global HANPP database provides information for up to 161 individual countries/regions for the period 1961-2005. For the years 1910, 1930 and 1950 data are only available for 11 world regions. For this paper we aggregated data and defined world regions according to geographic and additionally socio-economic criteria: Africa, Asia* (excluding the former Soviet Union), Latin America, Former Soviet Union and Eastern Europe (FSU-EE), Western Industrial. The region denoted as Western Industrial includes all Western European and North American countries as well as Australia and New Zealand.

Africa (incl. Western Asia)	**Northern Africa and Western Asia:** Algeria, Armenia, Azerbaijan, Cyprus, Egypt, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Libyan Arab Jamah., Morocco, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, Turkey, United Arab Emirates, Western Sahara, Yemen **Subsaharan Africa:** Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Rep., Chad, Dem. Rep. of Congo, Congo, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, United Rep.Tanzania, Togo, Uganda, Zambia, Zimbabwe
Asia* (Asia excluding the Former Soviet Union (FSU))	**Eastern Asia:** China, Japan, Korea,Dem.Ppl's.Rep., Korea, Republic of, Mongolia **Southern Asia:** Afghanistan, Bangladesh, Bhutan, India, Iran(Islamic Rep. of), Nepal, Pakistan, Sri Lanka **Southeastern Asia:** Papua New Guinea, Brunei Darussalam, Cambodia, Indonesia, Lao People's Dem. Rep., Malaysia, Myanmar, Philippines, Thailand, East Timor, Viet Nam
Latin America (incl. the Carribean)	**Latin America and the Caribbean:** Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Former Soviet Union and Eastern Europe (FSU-EE)	**Central Asia and Russian Federation:** Belarus; Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan **Eastern and South Eastern Europe:** Albania, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, T.F.Yug.Rep. Macedonia, Republic of Moldova, Poland, Romania, Yugoslavia, Slovakia, Slovenia, Ukraine
Western Industrial	**Western Europe:** Austria, Belgium-Luxembourg*, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom **Northern America:** Canada, United States **Australia and Oceania:** Australia, New Zealand

* not differentiated

2 Supporting Figures

S1A S1B

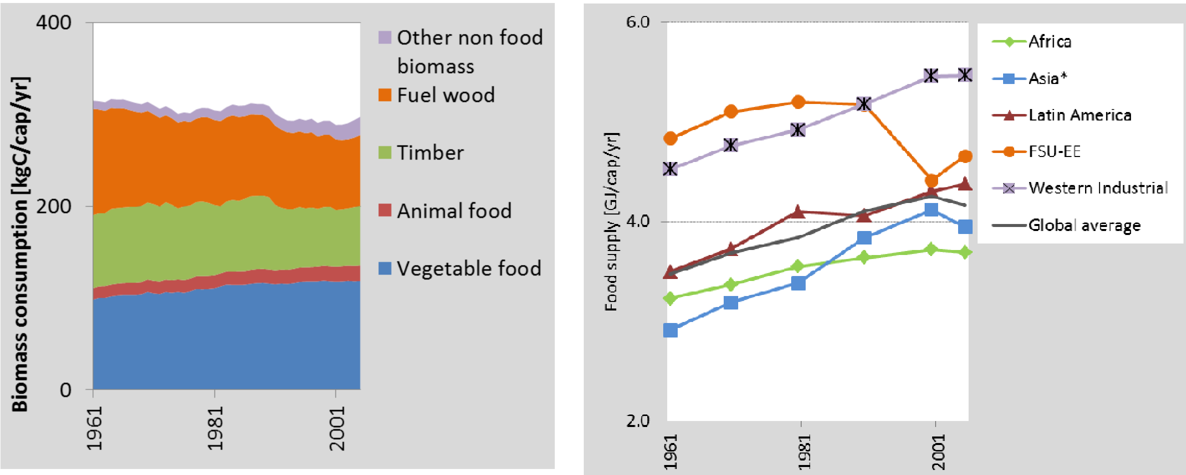
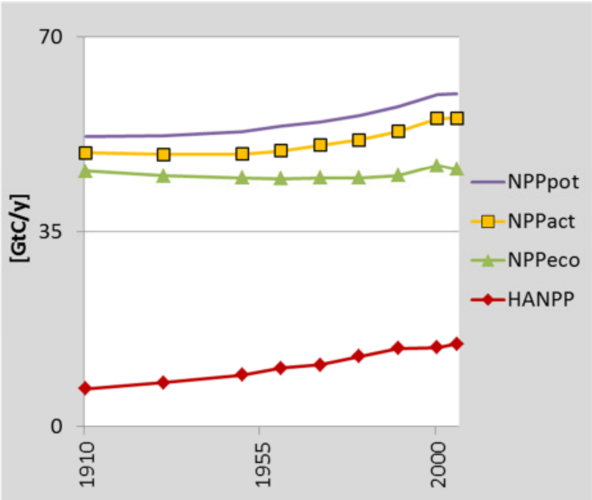


Figure S1: Consumption of biomass products in kg of carbon per capita and year (kgC/cap/yr) (S1A) and per capita food supply by world regions in gigajoule per capita and year (GJ/cap/yr) capita (S1B). The per capita consumption of final biomass products slightly declined in the second half of the 20th century. This is related to a shift in the patterns of the use of biomass products, above all reductions in the consumption of fuel wood. Food availability has improved considerably. Data from FAO (21) show that food supply per capita increased in all regions of the world with the exception of the FSU-EE region, where the agricultural production system collapsed after the breakdown of socialism in 1991. Final biomass consumption is calculated on the basis of FAO commodity balances (21).

S2A



S2B

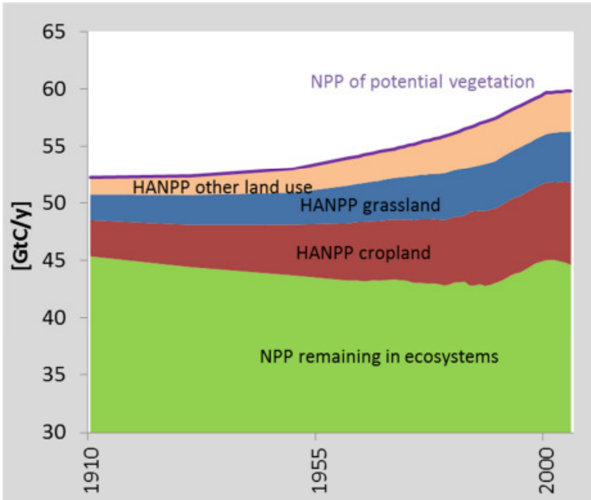


Figure S2: Development of NPP components (S2A) and HANPP by land use type (S2B) from 1910 to 2005 in gigatonnes of carbon per year (GtC/y). NPP_{pot} refers to the NPP of potential vegetation in the absence of land use, NPP_{act} to the NPP of the prevailing vegetation and NPP_{eco} to the NPP remaining in ecosystems after harvest. Figure S2 shows a 14% increase in total plant productivity potential (NPP_{pot}) from 52 GtC/y in 1910 to 59 GtC/y in 2005. This growth is a result of CO_2 fertilization and climate change as calculated by LPJmL. The flattening of the trend of NPP_{pot} after 2000 is due to large scale droughts and the high sensitivity of the LPJmL model to water stress. The flattening of the global aggregate is a result of low NPP_{pot} in Latin America and Oceania in these years. Satellite derived NPP estimates (74) confirm that in the period from 2000 to 2005 large scale droughts and a drying trend in the southern hemisphere have contributed to a regional decline in NPP.

Two positive and one negative force resulted in a modelled rise in total plant production (NPP_{act}) from 49 to 55 GtC/y (Fig. S2B), a trend also observed in satellite derived estimates (74). One positive factor has been the 14% increase in total plant productivity potential (NPP_{pot}) due to climate change and CO_2 fertilization as estimated by the LPJmL model. Although this growth level is uncertain for reasons explained in section 1.3, CO_2 fertilization may have contributed to rising NPP_{act} in forests and grasslands and may help to explain some of the rise in crop yields. Increasing crop yields provides a second positive factor, increasing total plant production on cropland (NPP_{act}) by 80% or 195 $gC/m^2/y$ of cropland and by 4.1 GtC/y globally in total (Fig. 2 in the main text). That led to a decline in $HANPP_{luc}$ per unit area of 118 $gC/m^2/y$. The increases result from management and, to a certain extent, possibly also to climate change. A negative factor results from the expansion of cropland and pasture because they have lower NPP than that of original vegetation even with the growth in crop yields. For this reason, even though $HANPP_{luc}$ per hectare declined substantially on cropland, total $HANPP_{luc}$ on all cropland declined only by 0.1 GtC/y or 6% (Fig. 2 in the main text).

Because of this rise in plant production, even as HANPP has more than doubled (rising 116%), we estimate that the total carbon left to ecosystems, NPP_{eco}, has remained approximately stable over this period (Fig. S2B). That does not imply an absence of adverse environmental effects. Overall, agricultural land has expanded by 28 million km² and the areas of forest harvest have roughly doubled in the last century (8, 75). This expansion would have contributed to a large decline in NPP_{eco} if not compensated by yield growth in cropland agriculture.

S3A S3B

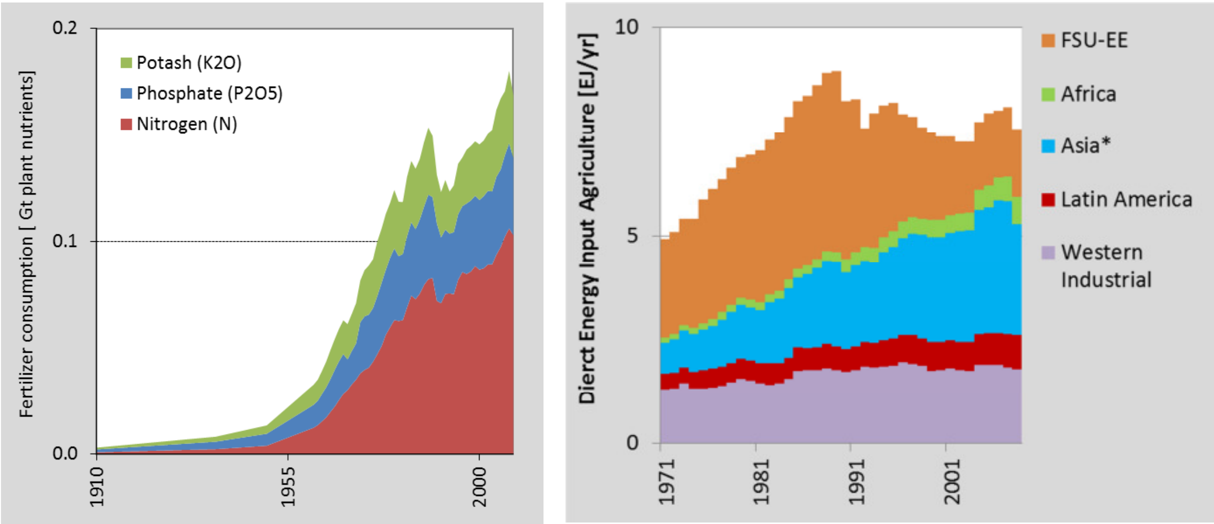


Figure S3: Development of fertilizer and direct energy use in agriculture. The divergence of HANPP and population growth was a result of agricultural intensification and was among others based on high inputs of (a) industrial fertilizers and (b) fossil energy. The slump of fertilizer and agricultural energy use in the 1990s was due to the collapse of the USSR and its agricultural production system. In 2005 direct energy use in agriculture amounted to 7.7 EJ, the energy required to produce 0.17 Gt of industrial fertilizer added another 5.6 EJ. Sources: Fertilizer data based on references (76) and (77); direct energy use in agriculture based on ref. (71); energy requirement for fertilizer production based on ref. (78).

3 Supporting Tables

	Population density [cap/km²]	Livestock [livestock units/cap]	Biomass consumption [kg/cap/y]	Net biomass trade [kg/cap/y]	$HANPP_{harv}/NPP_{pot}$ on cropland
Africa	33	0.38	582	78	43%
Asia*	165	0.25	441	24	80%
Latin America	28	0.89	801	-147	56%
FSU-EE	17	0.32	737	-51	56%
Western Industrial	25	0.50	1070	-126	89%
Global average	50	0.36	589	0	69%

Table S1: Factors influencing HANPP per capita (2005). Sources: Population density and livestock units per capita are based on data from ref. (21); biomass consumption refers to apparent consumption of biomass products (plant and animal based food, fibre, timber, fuel wood and other use of biomass) and is measured in kg dry matter based on FAO commodity balances and forestry statistics (21). Regional net-trade in biomass in kg dry matter per capita is derived from FAO agriculture and forestry trade data (21); negative values indicate net-exports. $HANPP_{harv}/NPP_{pot}$ on cropland indicates the efficiency of the agricultural production system.

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