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What determines geographical patterns of the global human appropriation of net primary production?

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The human appropriation of net primary production (HANPP) is an integrated socioecological indicator of the intensity of land use. HANPP is associated with changes in global biogeochemical cycles of carbon, water, nitrogen and other substances as well as in ecosystem functions, services and biodiversity. Understanding patterns in HANPP is therefore important for the integrated analysis of the global land system. Attempts to explain spatial patterns of HANPP need to take both socioeconomic and natural factors as well as their interaction into account. In order to contribute to the understanding of global geographical patterns of HANPP, we discuss here the statistical analysis of a global national-level data set that includes data on HANPP and its components as well as selected potential determinants of HANPP for the year 2000. This statistical analysis is complemented with a discussion of findings from long-term country-level case studies conducted by ourselves and our students. We find that HANPP is higher in naturally more productive countries. Population density emerges as the most powerful factor determining HANPP per unit area and even has a strong influence on national-level patterns in per-capita HANPP. The interrelation between HANPP and economic growth or development is complex. On the one hand, growing affluence is associated with richer diets and other consumption patterns that tend to drive up HANPP, but on the other hand, economic growth is also associated with growing biomass trade as well as technological innovations that can help to reduce the amount of HANPP caused per unit of biomass consumption. While drawing some preliminary conclusions from our analysis, we also underline the necessity for further research

Keywords: human appropriation of net primary production; socioeconomic drivers; land use; land system science

1. Introduction

The Global Land Project (GLP) aims at measuring and understanding patterns and dynamics of the global land system. The notion 'land system' was recently coined to underline the necessity to conceptualize the Earth's lands as coupled socioecological (or human–environmental) systems in order to foster understanding of the intricate interplay of both social and natural factors shaping patterns and dynamics of terrestrial systems (GLP 2005). Land change science 'seeks to understand the dynamics of land cover and land use as a coupled human-environment system to address theory, concepts, models and applications relevant to environmental and societal problems, including the intersection of the two' (Turner, Lambin, and Reenberg 2007).

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Basically, land is used by human societies for at least three core functions (Dunlap and Catton 2002): (1) resource supply, i.e. the provision of inputs for socioeconomic metabolism, including non-renewable ones like fossil fuels, minerals and other materials extracted from geological deposits and renewable ones like biomass or water diverted from current biogeochemical cycles ultimately driven by an influx of solar energy; (2) waste absorption as well as buffering and regulating capacities of ecosystems; and (3) space occupied for human infrastructures, including housing, gardening or recreational areas as well as industrial and transport facilities. Most human uses of land are dependent on the land's biological productivity, i.e. its net primary production (NPP) per unit area, and many land use activities aim at harvesting parts of the actual or accumulated NPP in the form of biomass derived through agricultural or forestry activities (Haberl, Wackernagel, Krausmann, Erb, and Monfreda 2004b). At the same time, land use often alters the land's productivity, thus resulting in a change in productivity denoted as ΔNPP_{LC}; that is, a change in NPP resulting from land conversion (Haberl *et al.* 2007). Moreover, agriculture and forestry – that is, human use of terrestrial ecosystems dominated by herbaceous or woody plants for biomass provision – entail the harvest of an often considerable fraction of the NPP. All these processes are captured in a measure called 'human appropriation of net primary production (HANPP)', defined as ΔNPP_{LC} plus NPP_h, where the latter is defined as the amount of NPP extracted by humans from an ecosystem or destroyed during harvest (e.g. roots of trees or agricultural crops killed during harvest).

HANPP has gained attention as an indicator that explicitly links natural with socioeconomic processes and thereby generates an integrated picture of socioecological conditions in the land system (Vitousek, Ehrlich, Ehrlich, and Matson 1986; Haberl 1997; Haberl *et al.* 2001; Rojstaczer, Sterling, and Moore 2001; Imhoff *et al.* 2004). Integrated analysis of socioecological conditions is a major goal of sustainability science (Kates *et al.* 2001; Kates and Parris 2003). HANPP relates to important global sustainability issues such as endemic malnourishment of a large proportion of the world population (FAO 2005b), the ongoing conversion of valuable ecosystems (e.g. forests) to infrastructure, cropland or grazing land (Millenium Ecosystem Assessment 2005; Lambin and Geist 2006) with detrimental consequences for biodiversity (Heywood and Watson 1995) and global, human-induced alterations of biogeochemical cycles (Crutzen and Steffen 2003; Steffen *et al.* 2004). The notion that HANPP was a straightforward indicator for ecological limits to growth (Meadows, Meadows, and Randers 1992; Sagoff 1995; Costanza, Cumberland, Daly, Goodland, and Norgaard 1998; Pimentel 2001) has meanwhile lost credit because (1) economic growth may proceed even without growing biomass use and (2) long-term studies of HANPP have shown that HANPP may decline even if biomass harvest grows as the productivity of vegetation rises because of agricultural intensification (Davidson 2000; Haberl *et al.* 2001; Krausmann 2001). Studies of global or regional HANPP have nevertheless gained considerable attention because of the interpretation of HANPP as a measure of human domination of ecosystems (Vitousek, Mooney, Lubchenco, and Melillo 1997). Moreover, recent empirical studies suggest that HANPP may be a potent indicator of pressures on biodiversity (Haberl *et al.* 2004a; Haberl *et al.* 2005).

One reason why HANPP can be useful for integrated analyses of socioecological systems is that it simultaneously depends on socioeconomic and natural processes and conditions and that its definition can be simultaneously seen from societal and ecological perspectives (Figure 1). From a societal perspective, the above-given definition of HANPP means that HANPP measures the combined effect of land conversion and harvest on biomass flows in terrestrial ecosystems of a defined area of land; in other words, the combined effect of human-induced land-cover change and land use. From an ecological perspective, HANPP

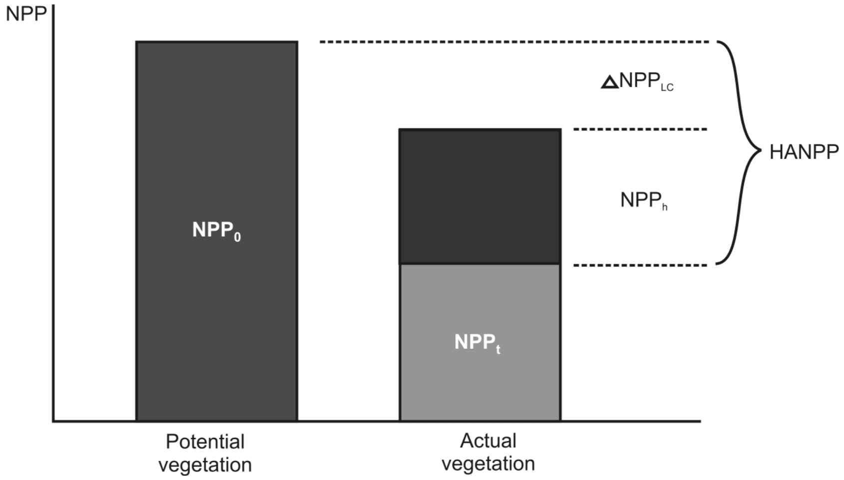


Figure 1. Definition of HANPP (Haberl 1997; Haberl *et al.* 2007). From an ecological perspective, HANPP can be defined as the difference between the NPP of the potential natural vegetation (NPP_0) and the NPP remaining in ecosystems after harvest (NPP_t). That is, it provides a measure of the impact of human activities on the availability of trophic energy in ecosystems. From a societal perspective, it measures the combined effect of land use-induced changes in NPP (ΔNPP_{LC}) and NPP extracted from ecosystems by biomass harvest for socio-economic use (NPP_h).

is a measure of the impact of land use on the availability of trophic energy (biomass) for heterotrophic food chains and as a resource for building up biomass stocks in terrestrial ecosystems used by humans. In that perspective, HANPP measures the changes in the amount of NPP remaining each year in ecosystems resulting from land use. From both perspectives, HANPP is indicative of the intensity with which humans use the land, but the socioeconomic perspective is focused on the activities causing change, whereas the ecological perspective is focused on the impact on the system under consideration.

A recent spatially explicit assessment of global HANPP (Haberl *et al.* 2007) has revealed distinct spatial patterns of HANPP across the globe, indicating the varying intensity of land use across the Earth's surface. Socioeconomic and natural factors that currently co-determine these spatial patterns of HANPP are at present only poorly understood, however. The purpose of this article is to summarize our knowledge on natural and socioeconomic determinants of HANPP and to establish a conceptual framework for studying spatial patterns of global HANPP. It combines expertise gained through global and national-level case study work with statistical analysis of national-level data on HANPP and some of its potential determinants. Figure 2 shows a scheme in which major potential influences and feedbacks are depicted in a 'wiring diagram' that here serves as a first attempt to systematize the various factors and to structure the remainder of this article. Accordingly, we proceed as follows. Section 2 gives an overview of the spatial pattern of global HANPP in the year 2000. Section 3 discusses natural factors potentially determining HANPP patterns, such as soil, clime or landform. Section 4 outlines the importance of socioeconomic factors such as population, socioeconomic metabolism, trade and technology. Section 5 includes a discussion of the material presented in the preceding sections, including some thoughts on co-regulation, and draws preliminary conclusions.

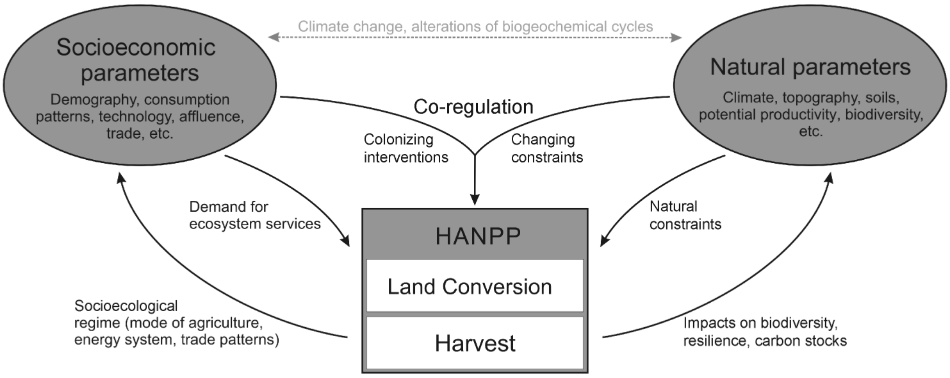


Figure 2. Wiring diagram of potentially relevant interaction processes between socioeconomic systems, natural systems and HANPP. HANPP patterns are thought to be simultaneously influenced by natural conditions and socioeconomic demand for ecosystem services and have socioeconomic as well as ecological implications. Over time, socioeconomic and natural conditions interact, resulting in a ‘co-regulation’ of HANPP.

2. Global human appropriation of net primary production patterns in the year 2000

It is the aim of this article to take a first step towards an integrated understanding of the natural and social determinants of HANPP patterns and their interaction. We proceed by analysing data from a recently published data set on HANPP and related parameters: This database includes spatially explicit (5’ geographic resolution, approximately 10 × 10 km at the equator) HANPP data for the Earth’s terrestrial biosphere (Haberl *et al.* 2007), a global 5’ land use data set consistent with cropland and forestry data of the FAO that was used in generating the HANPP data set (Erb *et al.* 2007) and detailed information on global socioeconomic biomass flows on a national level (Krausmann, Erb, Gingrich, Lauk, and Haberl 2008). Methodological issues related to data compilation and the calculation of HANPP are provided in detail in the original articles. Hence, we restrict ourselves here to provide some essential background information on how HANPP was calculated: As shown in Figure 1, HANPP estimates require information on NPP of the potential natural vegetation (NPP_0), land use-induced changes in NPP (ΔNPP_{LC}) and NPP harvested by humans (NPP_h). NPP_0 has been calculated with the Lund-Potsdam-Jena (LPJ) global vegetation model (Sitch *et al.* 2003). NPP_h is largely based on data provided by international agricultural and forestry statistics and ΔNPP_{LC} has been computed by combining data on land use derived from statistical and remote sensing sources and land use-specific productivity information based on yield data and LPJ.

We combine these data sets (which are available for download at http://www.uni-klu.ac.at/socec/inhalt/1088.htm) with data on population, economic productivity (gross domestic product, GDP) and a set of agricultural indicators derived from publicly available statistical databases (FAO 2005a). GDP data are given in US$ for the year 2000 converted according to purchasing power parities (PPP). As many of the data required to analyse potential socioeconomic drivers of HANPP are only available on the national level, we here analyse national-level data for 155 countries covering 98.5% of the global land mass. It is important to note that none of the data that have been used to calculate the independent variables used in the analysis (and in particular population density and GDP) has been used in the quantification of HANPP or related parameters.

Below, we discuss the regression analysis of HANPP and its potential drivers in which each data point represents one country. Countries with incomplete data coverage were kept in the overall sample but do not appear in the respective regressions; sample sizes (*N*) are therefore made explicit in discussing the statistical analysis. Logarithms were calculated for variables that were not normally distributed. Ordinary least-square regressions were performed using SPSS statistical software.

Table 1 shows an overview of global HANPP in the year 2000 and shows global totals of important socioeconomic biomass flows. It shows that global aggregate HANPP amounts to 31.2 petagrams dry matter biomass per year (Pg DM/year, 1 Pg = 10^{15} g = 10^9 t = 1 billion metric tons) which is 23.8% of the NPP of the potential terrestrial vegetation (NPP_0). ΔNPP_{LC} accounts for 40% of global HANPP. This measure includes changes in the productivity of ecosystems that result from current (e.g. soil sealing) or past (e.g. soil degradation) impacts on terrestrial ecosystems. Biomass harvest and human-induced fires account for 60% of global HANPP. As Table 1 shows, humans (respectively their livestock and machinery) harvest 12.14 Pg DM/year of biomass as crops, residues, wood and forage, the largest fraction being biomass grazed by livestock on grasslands. Only about two-thirds of NPP_h is actually processed by society: human-induced fires, felling losses, roots destroyed during harvest and unused residues on cropland – here denoted as 'unused extraction' – represent another significant human-induced biomass flow. Most of these flows, however, are directly related to biomass harvest, such as felling losses, residues and roots. To some extent, human-induced fires are also related to agricultural activities, for example, when forests are burned to facilitate land clearing or when agricultural residues are burned in the fields. Demand for biomass is thus not only a driver of 'used extraction' of biomass but also affects 'unused' extraction. Moreover, most ΔNPP_{LC} is also associated with biomass harvest, as most croplands and a considerable fraction of the grasslands used

Table 1. Components of global HANPP and global socioeconomic or human-induced biomass flows.

	NPP/biomass flow (Pg DM/year)	Percentage of NPP_0 (%)
Components of global HANPP		
NPP of the potential terrestrial vegetation (NPP_0)	131.02	100.0
NPP of the actually prevailing vegetation (NPP_{act})	118.44	90.4
NPP remaining in ecosystems after harvest (NPP_t)	99.82	76.2
Change in NPP resulting from land use (ΔNPP_{LC})	12.58	9.6
NPP harvested or destroyed (NPP_h)	18.62	14.2
HANPP (= ΔNPP_{LC} plus NPP_h)	31.20	23.8
Backflows to nature	4.92	3.7
Global human-induced biomass flows		
Used extraction of biomass[a]	12.14	9.3
Of which: harvested primary crops	3.43	2.6
Of which: harvested crop residues	2.93	2.2
Of which: grazed biomass	3.84	2.9
Of which: wood removals	1.94	1.5
Unused extraction[a]	6.48	5.0
Of which: human-induced fires	2.40	1.8
Of which: unused belowground biomass	1.92	1.4
Of which: unused residues on cropland	1.50	1.1
Of which: felling losses in forests	0.66	0.5

Sources: Haberl *et al.* (2007) and Krausmann *et al.* (2008).

[a] Used plus unused extraction equals NPP_h. 'Used' means that the biomass is further processed by society through biotic (food, feed) or abiotic (technical production) processes. 1 Pg DM is one Petagram dry matter biomass, 1 Pg = 10^{15} g = 10^9 t = 1 billion metric tons. 1 t dry matter biomass has a carbon content of approximately 0.5 t C.

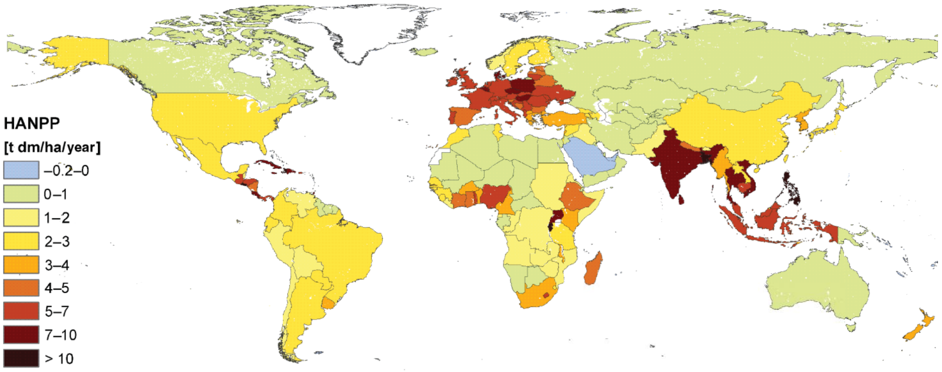
for biomass production were originally forests, and the agro-ecosystems resulting from land clearing are often much less productive than the forests they replace. About 92% (11.6 Pg DM/year) of the total ΔNPP_{LC} occurs on cropland and grazing land (the remainder on settlement and infrastructure areas) and is therefore also indirectly caused by biomass production.

Biomass demand used to feed livestock amounts to approximately 7 Pg DM/year, by far the largest component of socioeconomic biomass metabolism, and comprises not only grazed biomass, but also an increasing share of the high-quality primary crop products such as cereals and oil crops. Most of the feed is converted into protein-rich foods for human nutrition (meat, milk, eggs), but a significant share is required to feed draught animals in developing countries. Draught animals are, however, in most cases fed on crop residues or graze on marginally productive land rather than crops. The production of plant-based food products for human nutrition requires much less biomass: Roughly 1.5 Pg DM/year of primary crops is used for that purpose. With a bit over 50% of that amount, cereals (rice, wheat, corn) are the largest fraction. Animal-based biomass used for human nutrition amounts to 0.34 Pg DM/year, a tiny amount compared to the huge mass of biomass fed to animals. According to current estimates, the use of fuel wood amounts to between 1.0 and 1.8 Pg DM/year. In recent years, increasing amounts of biomass are produced in order to generate heat or power. Biomass for other industrial uses (i.e. excluding the industrial production or use of food, feed and fuel) is the third, and in quantitative terms least important component of global biomass demand. Industrial use of biomass includes the production of textiles, paper, wood products and biomass used in the chemical industry. The quantitatively most important flow is the extraction of wood for paper and timber (roughly 0.75 Pg DM/year).

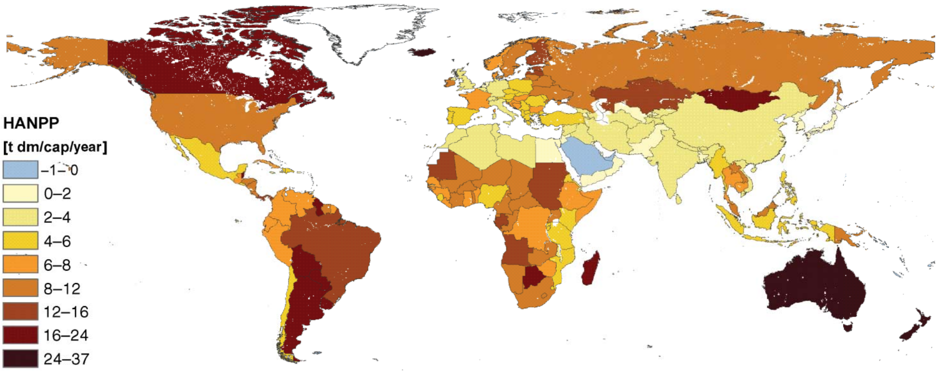
Current spatial patterns of global HANPP as visible on the national level are shown in the maps of Figure 3. Figure 3a reveals the large differences in the average HANPP per unit area, measured in t DM/ha/year, of different countries and regions. HANPP per unit area is the largest in South and South-East Asia as well as in Europe and much lower in the USA, Australia and the Russian Federation. It is important to note that HANPP per unit area may be low because of low intensity of land use compared to the productive potential of the land, or because of low productive potential of the land caused by, for example, aridity or low temperatures. Figure 3b shows that the picture changes completely if we look at the average HANPP per capita and year. For example, in Canada, HANPP is low per unit area, but very high per capita of population. A similar pattern can be found in Australia, much of South America, many African countries and in Mongolia. The population density map (Figure 3c) suggests that per-capita HANPP is low in densely populated countries or regions, e.g. Europe, China or India, a pattern that is analysed in more detail below.

It is also important to note that the averages shown in Figure 3 may give a somewhat distorted picture, in particular in large countries with considerable regional variation such as the USA, Canada, Russia, Brazil, Australia or China. Large, rather unproductive areas such as deserts or arctic tundra cover a considerable fraction of the territory of those countries. Gridded maps, such as those available in Haberl *et al.* (2007), are of course much more informative, but as most socioeconomic data required for the analysis presented below were not available on a more finely resolved level, we here work with what we had. As a next step, county- or even pixel-level data could be brought in to refine the picture. Doing this was beyond the scope of this article because of the immense amount of data work required for such an approach.

(a) HANPP per hectare and year



(b) HANPP per capita and year



(c) Population density (cap/km^2)

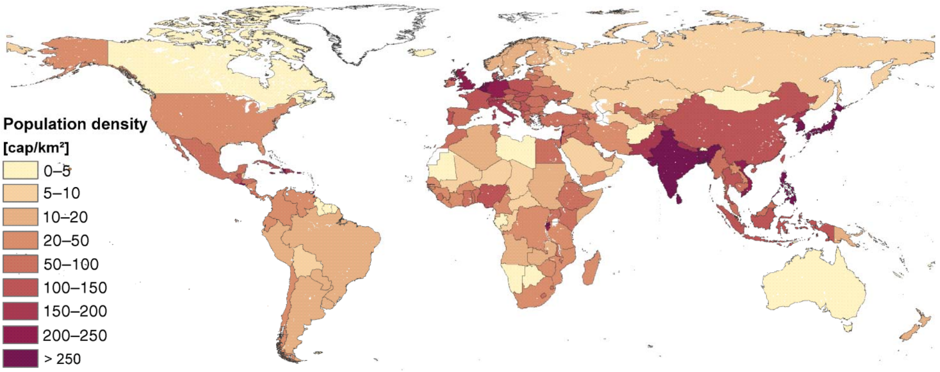


Figure 3. National-level maps of global HANPP and population density: (a) average HANPP per unit area (t DM/ha/year); (b) average HANPP per inhabitant (t DM/cap/year); and (c) population density (cap/km^2). Available in colour online.
Note: White areas: no data.

3. Soil, climate and landform as determinants of human appropriation of net primary production patterns

One bundle of factors that can be assumed to influence HANPP patterns is the suitability of land for human cultivation: its natural productivity, determined mostly by soil and climate conditions, and the dominant landforms. Flat areas are obviously much more easily used for agriculture or settlements than steep slopes. A landscape-scale study has shown that small-scale HANPP patterns (assessed in that case on a 1 × 1 km grid for a study area sized 2860 km^2 in central Austria) are highly significantly correlated with landform indicators such as altitude, slope and terrain roughness (Wrbka *et al.* 2004). Globally, and on coarser scales (e.g. at a geographic resolution of 0.5 × 0.5 degrees or even the national level discussed here), however, most researchers assume that the suitability of land for cultivation is largely a function of climate and soil properties (Cramer and Solomon 1993; Leemans and Solomon 1993; Ramankutty, Foley, Norman, and Mcsweeney 2002). One very important climate indicator is the length of the growing season that may be assessed by calculating simple indicators such as the number of 'growing degree days' (i.e. days with a base temperature above 5°C). Solar energy input is also critical; it mostly depends on geographic latitude and the number of sunshine hours. Precipitation is in many cases the decisive factor, as NPP is limited by water availability in a significant part of the terrestrial biosphere. While simple models such as Lieth's 'Miami model' (Lieth 1975) use readily available indicators such as total annual precipitation (mm/year) or mean annual temperature (°C), more sophisticated approaches are based on calculations of the availability of water to plants using the moisture index (actual evapotranspiration divided by potential evapotranspiration). The suitability of soil for cultivation can be modelled as well based on existing global soil databases using indicators such as soil carbon density and soil pH (Ramankutty *et al.* 2002).

Because of restrictions in data availability, and also in order to be consistent with the country-level analysis reported below, we use here a simpler approach: We take the productivity of potential vegetation, i.e. NPP_0, as a proxy of the productive capacity of terrestrial ecosystems within a country. NPP_0 strongly depends on the factors discussed above, i.e. the number of growing degree days, water supply, and soil quality. Of course we are aware that factors such as steep slopes or fragile soils, such as in tropical rain forests, may limit the suitability of land for cultivation even in cases where NPP_0 is high and that this may introduce some bias in our analysis. Despite these caveats, we found a strong positive correlation between NPP_0 and HANPP per unit area (Figure 4a). As can be expected, there is some amount of variation to be explained by other, predominantly socioeconomic factors, but the data suggest a significant tendency towards higher HANPP per unit area in more productive nations. Low initial productivity obviously constrains HANPP per unit area, and with higher NPP_0 it largely depends on other factors such as how intensively the productive potential of the land is used. We find almost no correlation between NPP_0 and population density, underlining the importance of factors that weaken the relation between productive potential and population density such as the history of the spread of *Homo sapiens*, the duration of continuous cultivation, urbanization, agrarian–industrial transitions and differences in biomass consumption patterns as well as in agricultural technology and biomass trade (de Vries and Goudsblom 2002). This result is consistent with the notion that the relationship between population growth and agricultural production is indeed very complex and depends on systemic interrelations between climatic and biogeographical conditions, land use, economic structures, technology and social organization (Boserup 1965, 1981).

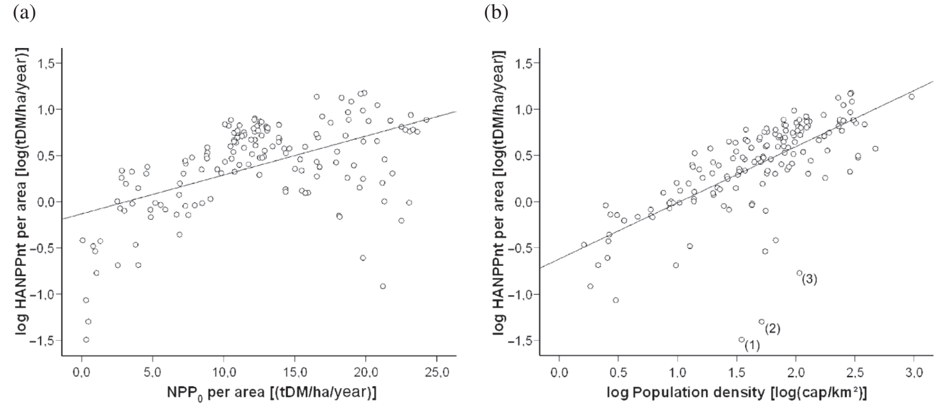


Figure 4. Scatter plot of the dependency of HANPP per unit area on (a) a country's productive potential (approximated as NPP_0/ha/year). $R^2 = 0.28$, $N = 153$, $p < 0.001$, and on (b) population density $r^2 = 0.50$, $N = 153$, $p < 0.001$.

Notes: Outliers in (b) are 1 – Yemen, 2 – Qatar, 3 – Kuwait; these countries are characterized by low NPP_0 because of the arid climate, considerable NPP increases because of irrigation and massive biomass imports.

4. Biomass demand and patterns of human appropriation of net primary production

The maps shown in Figure 3 suggest that population density is a major driver of HANPP per unit area. This is plausible because the amount of HANPP per unit area and year is, by definition, the product of HANPP per capita and year, and population density and population density varies between countries by a factor of over 700, whereas per-capita HANPP is less variable, varying between countries by a factor of 40:

$$\text{HANPP per unit area (t DM/ha/year)} = \text{population density (cap/ha)} \times \text{HANPP per capita (t DM/cap/year)}.$$

Regression coefficients between the logarithm of population density and selected other parameters are shown in Table 2. All indicators of biomass flows per unit area (biomass harvest, final biomass consumption and HANPP) are strongly and positively correlated with population density (the residuals are because of variation in per capita figures). Even if measured as the percentage of NPP_0, HANPP is still strongly correlated with population density. Economic indicators such as biomass trade (import/export/net trade) and GDP, if measured per unit area, are also strongly correlated with population density. The same holds for indicators of agricultural technology (fertilizer input and tractors per unit area) and livestock rearing intensity (livestock units per hectare). The only indicator in our sample that seems to be uncorrelated with population density is the share of animal products in diet, an affluence indicator that is strongly and positively correlated with GDP and the Human Development Index (HDI; see below), which is plausible because rich countries are able to procure protein-rich diets through imports irrespectively of population density. It is interesting to note that there is a strong and positive correlation between the ratio of final biomass consumption and HANPP per unit area and population density. This indicator shows how much HANPP is required in each country per unit of final biomass consumption; in other words, it is an indicator of the efficiency with which a country uses the productive potential of its territory. This result therefore suggests, quite plausibly, that low area availability

Table 2. Regression coefficients between the logarithm of population density (cap/ha) and selected other parameters.

	Pearson's r	Number of countries in sample (N)
Log biomass harvest (NPP_h) per hectare (t DM/ha/year)	0.75*	155
Log final consumption of biomass per hectare (t DM/ha/year)	0.93*	155
Log HANPP (% of NPP_0)	0.74*	153
Log HANPP per hectare (t DM/ha/year)	0.70*	153
Log net biomass trade per hectare (t DM/ha/year)	0.65*	97
Log biomass import per hectare (t DM/ha/year)	0.73*	150
Log biomass export per hectare (t DM/ha/year)	0.50*	150
Log GDP per hectare (US$/ha)	0.65*	153
Percentage of animal food (%)	−0.09	150
Log livestock units per hectare (LU/ha)	0.74*	153
Log fertilizer per hectare (kg N/ha/year)	0.33*	148
Log tractors per hectare (number of tractors/ha)	0.52*	155
Log final biomass consumption per unit of HANPP	0.54*	153

Note: *Significant at $p < 0.001$; no asterisk – not significant.

(= high population density) induces a higher efficiency of biomass production and use (cf. Boserup 1965, 1981).

In summary, population density is by far the strongest factor determining patterns of HANPP per unit area on a national level because of the enormous variation in population density in the different countries of the world (Figure 4b). Note, however, that sub-national patterns – as visible in gridded HANPP maps such as those included in Haberl *et al.* (2007) – do not strictly follow gridded population density maps: In urban areas, HANPP is often lower than on croplands; HANPP is therefore highest in intensively cropped areas and lower in urban areas (except in dense city centres), primarily grazed areas and forested land, and lowest in semi-natural or even natural areas. By contrast, population density is obviously by far highest in urban areas and much lower in many cropland-dominated rural areas.

In order to better understand the part of the variation in HANPP that cannot be explained by population density, we now focus on discussing the question of what determines patterns in HANPP per capita and year. We assume that per-capita HANPP is a function of affluence, technological efficiencies in the land-use and biomass-flow systems and biomass trade:

$$\text{Per-capita HANPP } = f(\text{affluence, technology, trade}).$$

As measures of affluence we use here both the GDP (given in US$/cap/year converted using PPP) and the HDI, a composite index that includes indicators of life expectancy, literacy, schooling and purchasing power. As trade indicators we calculated net trade, import and export of biomass (t DM/cap/year). As technology indicators we use fertilizer use (t N/cap/year) and tractors (number of tractors/cap).

Just like in the case of Austria (Haberl *et al.* 2004a; Haberl *et al.* 2005) we find very strong correlations between biomass harvest (NPP_h) and HANPP (Figure 5a), and the correlation between ΔNPP_{LC} and HANPP (not shown) is also positive and very strong ($r^2 = 0.78$, $N = 137$, $p < 0.001$). A somewhat weaker correlation is found between per-capita final biomass consumption and NPP_h (Figure 5b). Although the amount of biomass consumed per capita and year in a country influences the amount of biomass harvested

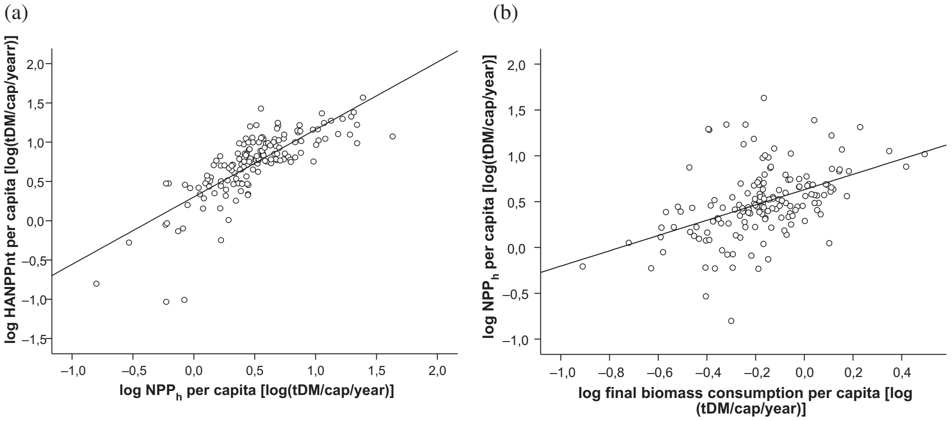


Figure 5. Scatter plots of the correlation between (a) per-capita NPP_h and HANPP (both in t DM/cap/year), $r^2 = 0.61, N = 153, p < 0.001$, and (b) per-capita final biomass consumption and NPP_h (t DM/cap/year), $r^2 = 0.21, N = 155, p < 0.001$.

(NPP_h) on its territory, this interrelation is weaker because the amount of biomass flows lost during harvesting and processing varies considerably, and also depends on the structure of final consumption (e.g. a higher proportion of animal protein in final consumption can greatly increase the relation between final biomass consumed and NPP_h). Biomass trade of course also affects this interrelation. In other words, consumption patterns, technology and trade determine the interrelation between final biomass consumption and NPP_h as well as HANPP.

A quite counterintuitive finding of our analysis (Table 3) is that there are no significant correlations between affluence or development, measured by GDP and HDI, and the amount of HANPP per capita and with per-capita biomass harvest, both measured as tons dry matter biomass per capita and year (t DM/cap/year). According to our expectations, we find some correlation between final biomass consumption and economic activity and development

Table 3. Regression coefficients (Pearson's *r*) and number of countries (*N*) in the respective sample for correlations between the logarithm of per-capita GDP ($/cap/year) and the HDI and selected other parameters.

	GDP		HDI	
	r	*N*	*r*	*N*
Animal protein as percentage of total food intake (%)	0.77**	149	0.81**	124
Log fertilizer use per capita (t/cap/year)	0.62**	147	0.72**	121
Log number of tractors per capita (#/cap)	0.64**	153	0.76**	130
Log net biomass trade per capita (t DM/cap/year)	0.70**	95	0.70**	79
Log biomass import per capita (t DM/cap/year)	0.85**	149	0.80**	129
Log biomass export per capita (t DM/cap/year)	0.67**	146	0.65**	129
Log final biomass consumption per capita (t DM/cap/year)	0.34**	153	0.26*	125
Log final biomass consumption per HANPP (%)	0.24*	151	0.17	123
Log livestock units per capita (LU/cap)	0.05	153	0.02	125
Log biomass harvest (NPP_h) per capita (t DM/cap/year)	0.01	153	−0.03	125
Log HANPP per capita (t DM/cap/year)	−0.04	151	−0.03	123

Note: *Significant at $p < 0.05$; **Significant at $p < 0.001$; no asterisk – not significant.

status, but this correlation is also rather weak (Table 3). This puzzling result will be explored in the following discussion, as it runs counter the simple assumption that the final demand for biomass products by households and industry were driven by economic activity and development and would thus largely determine the amount of biomass harvested on a country's territory and therefore of its HANPP.

We therefore again look at the importance of population density as a decisive factor of per-capita HANPP. We find a strong negative correlation between population density and per-capita HANPP (Figure 6a) as well as between population density and biomass harvest per capita (Figure 6b), thus supporting the findings of earlier studies (Weisz *et al.* 2006; Krausmann *et al.* 2008) that also underlined the importance of resource endowment, in this case the availability of bioproductive area, as a determinant of per-capita biomass flows. It seems that population density (or rather its inverse, land availability) has had a strong influence on consumption patterns, historically evolved production and consumption patterns are still influencing levels and structure of per-capita biomass use. For example, the rice-based diets of densely populated countries like Japan or Korea with a comparatively low share of animal protein are associated with a much lower level of per-capita biomass harvest as the meat-rich diet of sparsely populated North and Latin American countries such as the USA or Argentina (cf. Grigg 1995).

Despite its limited scope, our database provides some further evidence that is useful in analysing the complex interdependencies at hand. One of the strongest correlations in our analysis (Table 3) is that between the share of animal protein in total food intake and both GDP and HDI, suggesting that economic growth and development are strongly related to improvements in diet. The agricultural technology indicators in our database – nitrogen use per capita and year, number of tractors per capita – are also strongly correlated with both GDP and HDI, suggesting that agricultural intensity is strongly correlated with economic development, despite all efforts to disseminate agricultural technology to developing countries during the 'green revolution'. Similarly, strong correlations can be found between the two development indicators and net biomass trade and also its components, biomass import and biomass export. This indicates that the lacking overall correlation between affluence and

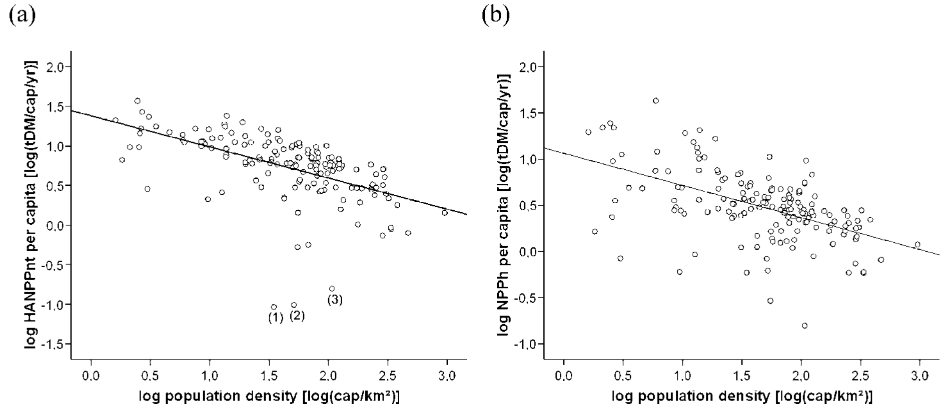


Figure 6. Scatter plots of the correlations between population density and (a) HANPP per capita (t DM/cap/year), $r^2 = 0.30$, $N = 153$, $p < 0.001$, (b) per-capita biomass harvest (NPP$_h$, measured as t DM/cap/year), $r^2 = 0.27$, $N = 155$, $p < 0.001$.

Notes: Outliers in (a) are 1 – Yemen, 2 – Qatar, 3 – Kuwait; these countries are characterized by low NPP$_0$ because of the arid climate, considerable NPP increases because of irrigation and massive biomass imports.

per-capita HANPP may be explained through the interaction of technology factors and international trade which systematically co-vary along GDP and HDI gradients as discussed in detail below.

5. Discussion and conclusions

The above-discussed evidence suggests that analysing the interrelations between socio-economic development or affluence, HANPP and biomass metabolism is a complex task because key factors such as regional biomass production systems, consumption patterns, population and technology change in a co-evolutionary process during agrarian–industrial transitions, i.e. transitions from agrarian subsistence economies to fossil fuel-based industrial market economies (Fischer-Kowalski and Haberl 2007; Krausmann *et al.* 2008) and therefore along GDP and HDI gradients. It is exactly this bundle of highly interrelated factors that determines how HANPP on national territory is related to affluence, biomass flows and land use. Moreover, resource endowment, i.e. the availability of productive land suitable for cultivation, seems to affect the specific trajectories during agrarian–industrial transitions. It seems plausible that countries with a very high population density will have to import a higher share of their biomass and develop highly intensive forms of cultivation, whereas sparsely populated countries will usually also use the option to extend farmland areas instead of using intensive technology. In order to complement the above-discussed statistical analysis, we also include in the following discussion insights gained in various long-term country-level case studies (e.g. Krausmann 2001, 2004; Haberl and Krausmann 2007; Kastner 2007; Krausmann and Haberl 2007; Schandl and Krausmann 2007; Musel 2008; Schwarzlmüller 2008).

Figure 7 shows an overview of the systematics and interrelations between the different factors that influence geographical patterns of HANPP according to our current knowledge. Although the magnitude and composition of final biomass demand has to be regarded as a major driver of HANPP, our analysis has shown that the relation between national HANPP and final biomass consumption is rather weak ($r^2 = 0.22$, $N = 153$, $p < 0.001$) because of two major intervening variables: (1) technology determines the efficiency of land use and the biomass conversion system and therefore strongly affects the ratio between final biomass consumption and the amount of HANPP resulting from that consumption; and (2) international trade allows for a decoupling of national biomass consumption and domestic HANPP.

Technology has a profound effect on the amount of HANPP required per unit of final biomass demand (Krausmann 2001). The production of one unit of biomass for final consumption requires a certain amount of primary biomass harvest (e.g. feed for the production of meat) which, in turn, is associated with a certain amount of unused extraction (e.g. crop residues). The ratio of both used and unused 'upstream' biomass flows required per kilogram of a specific final biomass product varies according to prevailing technology. For example, the amount of feed required to produce 1 kg of meat is highly variable across countries with different production systems and climate conditions as well as across time. The same holds true for many other factors, including losses during harvest or in production chains (Smil 2000; Gerbens-Leenes and Nonhebel 2002; Wirsenius 2003). According to our database, the average ratio between NPP_h and final biomass consumption varies between countries by a factor of 25 (Krausmann *et al.* 2008).

The amount of primary biomass that can be harvested per hectare and year is also technology dependent and highly variable across countries and over time. Intensification based on increases in the inputs of labour, machine power, fertilizers or irrigation can considerably increase the amount of biomass production per unit of land. Under these

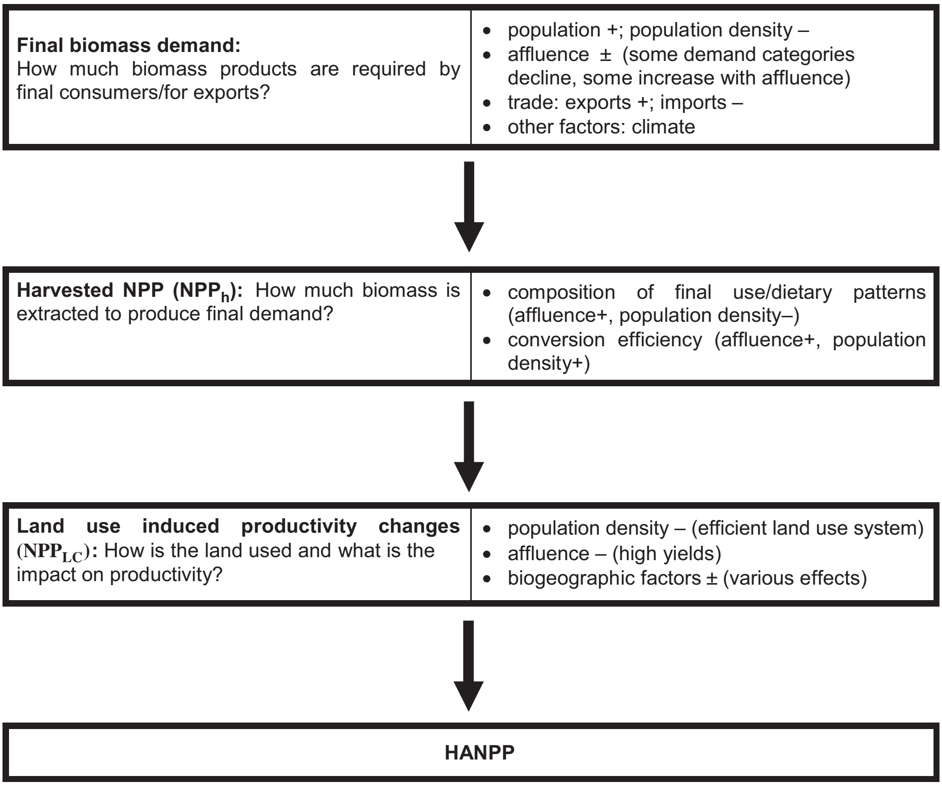


Figure 7. Systematics of the factors influencing geographical patterns of HANPP. A nation's HANPP results from the supply of biomass products for final consumption and exports. Domestic production of biomass products requires biomass extraction (NPP_h) and results in land use-induced changes in NPP (ΔNPP_{LC}). The relation between final biomass demand and HANPP is influenced by a number of co-varying factors that may have opposing effects. The most significant individual variable influencing HANPP is population density (i.e. the inverse of resource endowment). Population density influences the level and structure of biomass use in a country as well as the efficiency of biomass conversion and of the land use system. Affluence, technology and international trade are highly interrelated factors that co-determine the geographical pattern of HANPP.

circumstances an increase in NPP_h does not necessarily result in an increase of HANPP because it can be accompanied by a decrease in $\Delta NPP_{LC.}$ As a consequence, the area efficiency of the land use system – that is, the amount of biomass gained for human consumption per unit of HANPP – increases with intensification, whereas other indicators, such as the energy return on investment, deteriorate (Pimentel 2001). Again, lack of resource endowment is a strong driver of efficiency gains. NPP_0 per capita is an even better proxy of resource endowment than area availability (i.e. the inverse of population density) because it reflects the productive capacity of the ecosystems in a country. We find a strong negative correlation between per-capita NPP_0 and the efficiency of the aggregate land-use/biomass-flow system as measured by the ratio between final biomass consumption and HANPP (Figure 8a), suggesting that measures to increase the efficiency of this system are only taken when land is scarce. This even holds for the system's components. In Figure 8b, we show a strong positive correlation between resource endowment (NPP_0/cap/year) and productivity

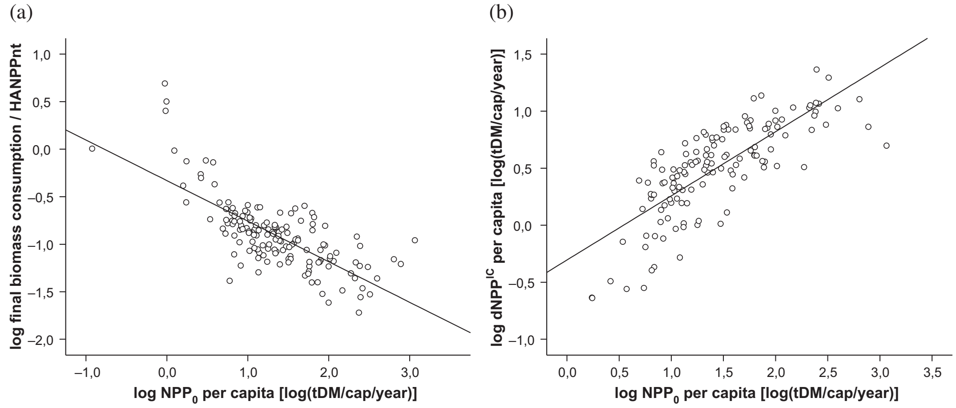


Figure 8. Scatter plots of the correlations between the logarithm of per-capita NPP_0 (measured as t DM/cap/year) and (a) the logarithm of the ratio between final biomass consumption and HANPP on national territory (dimensionless), $r^2 = 0.54$, $N = 153$, $p < 0.001$ and (b) the logarithm of ΔNPP_{LC} (measured as t DM/cap/year), $r^2 = 0.60$, $N = 137$, $p < 0.001$.

losses because of land conversion (ΔNPP_{LC}), implying that countries with low resource endowment cannot afford to waste productive capacity of their ecosystems by allowing the NPP of the actually prevailing vegetation (NPP_{act}) to drop far below NPP_0.

Consequently, the aggregate impact of rising biomass consumption on HANPP may be much smaller than its impact on NPP_h, in fact, it is even possible that NPP_h rises while HANPP decreases, as was, for example, the case in Austria 1830–2000. In particular, the intensification of agriculture and forestry related to the industrialization of agriculture during the green revolution after the Second World War resulted in stable or even slightly declining relative HANPP values despite a 75% increase in the amount of biomass harvested (Krausmann 2001). Similar patterns were found in other long-term case studies on the Philippines, the UK and Spain (Kastner 2007; Musel 2008; Schwarzlmüller 2008). For this reason, countries with very intensive land use systems (high biomass yields per unit area) may show a low or moderate level of HANPP despite a high level of biomass harvest per unit area and year. Both the intensity of the land use system and the efficiency of biomass conversion are related to population density (and income). Densely populated countries in general have developed intense land use systems characterized by high yields and comparatively low ΔNPP_{LC}.

Increasingly, the integration into global markets and international trade with biomass products is superimposed on the relation between patterns of final biomass consumption and HANPP in a country. Although many biomass products have a long history of long-distance trade (silk, olive oil, wine), there is a strong historical linkage between local consumption patterns and local HANPP patterns. This has changed since the onset of the industrial revolution. Industrialization changes both the agricultural production system and offers new possibilities of long-distance transport of bulk biomass flows. This increasingly releases the strong historical linkage between local demand, local land use and HANPP patterns. Consequently, global trade with biomass products becomes a major factor linking local human demand with biomass extraction and HANPP in distant regions. For example, the average distance of British biomass imports tripled during the nineteenth century to 10,000 km (Peet 1969); transport intensity of Austrian biomass imports increased from 6 to 17 billion ton kilometres between 1950 and 2000 (Haberl and Krausmann 2007). During the last 40 years, the growth of globally exported biomass followed a linear trend and grew by a factor 4.7 (own calculations based on FAO 2005a).

Although still only a comparably small amount of biomass (5%) is traded internationally as compared to the total extraction of used biomass, trade has to be considered an important driver of HANPP and its spatial patterns: Traded biomass products are associated with a large upstream harvest of used and unused biomass and HANPP induced by land use change: 1 kg of imported pork requires 5–10 kg of primary biomass for its production which in turn is associated with 2–4 kg of unused extraction and to HANPP related to land-cover change in the exporting country. The impact of trade on global HANPP patterns is therefore much larger than the small amount of traded biomass quoted above suggests. In a world with a rapidly globalizing economy and a large fraction of the population living in urban centres, local demand structures are less and less related to local HANPP patterns. This delinking between the pattern of consumption and production can be expected to increase.

In countries which are highly involved in international trade with biomass products, trade may substantially alter the interrelations between consumption patterns, the local land use system and HANPP. In the year 2000, roughly 90 countries (out of 155) were net importers of biomass and were externalizing up to 90% of the HANPP associated with their biomass consumption. Countries depending on high net imports of biomass may have a comparatively low HANPP because they are externalizing the impact of their consumption on ecosystems. In other countries, large net exports contribute to relative higher levels of domestic HANPP. The volume of per-capita imports and exports is closely correlated to GDP/cap; the higher the income the higher both imports and exports of biomass products.

Although our analysis has shown that national patterns of HANPP are a product of a complex bundle of factors, we could identify a number of mostly interrelated key variables that explain much of the cross national differences in biomass demand and associated HANPP: While population density (or its inverse, land availability) is the most significant individual variable determining differences in per-capita HANPP across countries also affluence, agricultural technology and international trade influence HANPP or HANPP components in various and not unidirectional ways. We conclude that further analyses are desirable to better understand the complex interdependencies at hand. An improved understanding of the natural determinants of HANPP will require a higher spatial resolution and additional indicators on soil, landform and climate. However, socioeconomic factors must be considered in such analyses as well, which is not easy at the sub-national level because many socioeconomic data are not, or at least not readily, available with the required resolution. We also think that a set of carefully selected long-term country-level case studies could help to derive and test causal models of the determinants of HANPP and its components that may prove helpful in corroborating the interdependencies discussed above. Such case studies therefore seem imperative in order to gain an improved understanding of the socioecological interactions involved in determining global HANPP and therefore in being able to reconstruct its past development and project its possible future trajectories.

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