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Human appropriation of net primary production (HANPP)

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1. Introduction

Humanity's impact on the biosphere's structures (e.g., land cover) and functioning (e.g., biogeochemical cycles) is considerable. It exceeds natural variability in many cases (Crutzen and Steffen, 2003). Up to 83% of the global terrestrial biosphere have been classified as being under direct human influence, based on geographic proxies such as human population density, settlements, roads, agriculture and the like (Sanderson et al., 2002, p. 892); another study estimates that about 36% of the Earth's bioproductive surface is "entirely dominated by man" (Hannah et al., 1994).

HANPP, the "human appropriation of net primary production," is an aggregated indicator that reflects both the amount of area used by humans and the intensity of land use. HANPP measures to what extent land conversion and biomass harvest alter the availability of trophic (biomass) energy in ecosystems. It is a prominent measure of the "scale" of human activities compared to natural processes (i.e. of the "physical size of the economy relative to the containing ecosystem;" Daly, 2006, p.1). As human harvest of biomass is a major component of HANPP, it is also closely related to socio-economic metabolism (Ayres and Simonis, 1994, Fischer-Kowalski and Haberl, 1997) as measured by material flow accounts (MFA; see e.g. Hinterberger et al., 2003, Weisz et al., 2006).

The basic question of how much of the biosphere's yearly biomass flows is used by humans was first posed in the 1970s (Whittaker and Likens, 1973), and it took more than a decade until the first comprehensive – and still relevant – answer to that question was given (Vitousek et al., 1986). This entry gives an overview of the research that has followed these seminal statements and proceeds by discussing issues of definition (section 2), presenting some basics on methodology (section 3) and giving an overview of the current knowledge on global HANPP (section 4). This is followed by a concluding section on interpretation and further research requirements (section 5).

2. Definition of HANPP

Just like any other scientific concept, HANPP has to be rigorously defined, and different definitions may lead to substantially different empirical results. And just like in any new, innovative scientific field, different authors have approached HANPP from different angles and have consequently used a variety of definitions. Unfortunately, however, this lack of standardization has resulted in a range of empirical results (discussed below), thus creating the impression as if it were very difficult, maybe even impossible, to assess HANPP with sufficient accuracy. This has not only hampered the comparability of results but has also fueled critiques that might eventually jeopardize the credibility of the whole concept (Davidson, 2000, Rojstaczer et al., 2001). This section gives an overview of the different definitions used so far. Harmonization of HANPP definitions seems therefore highly important.

Vitousek et al. (1986) calculated HANPP using three different possible definitions, each of which is a measure of a different process or pattern. First, they assessed only biomass directly used by society (food, timber, etc.). Second, they added the net primary production (NPP) of human-dominated ecosystems (e.g. croplands). Third, they additionally considered the NPP lost due to human-induced changes in ecosystem productivity, e.g. ecosystem degradation.

Wright (1990) proposed to define HANPP as the difference in NPP available in (hypothetical) undisturbed ecosystems and the amount of NPP actually available to support heterotrophic food chains. He excluded activities such as logging and biomass burning in forests on the grounds that they do not result in a long-term reduction of productivity of the land for wild species if forests are allowed to regrow (Wright, 1990). There is ample evidence, however, that harvest and biomass burning are very important for forest ecology (Harmon et al., 1986, Harmon et al., 1990). NPP appropriated in forests through timber harvest and related processes should therefore be included in any definition of HANPP.

A later study of global HANPP (Rojstaczer et al., 2001) focused on uncertainty and, in doing so, only considered Vitousek's second definition. A recent study (Imhoff et al., 2004) calculated the global human consumption of NPP – something quite different from Vitousek's original concept – but labeled the resulting figures also as „HANPP." The definition used in this latter paper was between the first two definitions of Vitousek: It did not include the total NPP of human-dominated ecosystems, but parts of plants not actually harvested were considered if they were required for producing the harvested material (e.g. roots). Neither Rojstaczer et al. (2001) nor Imhoff et al. (2004) considered changes in NPP caused by past or present land use.

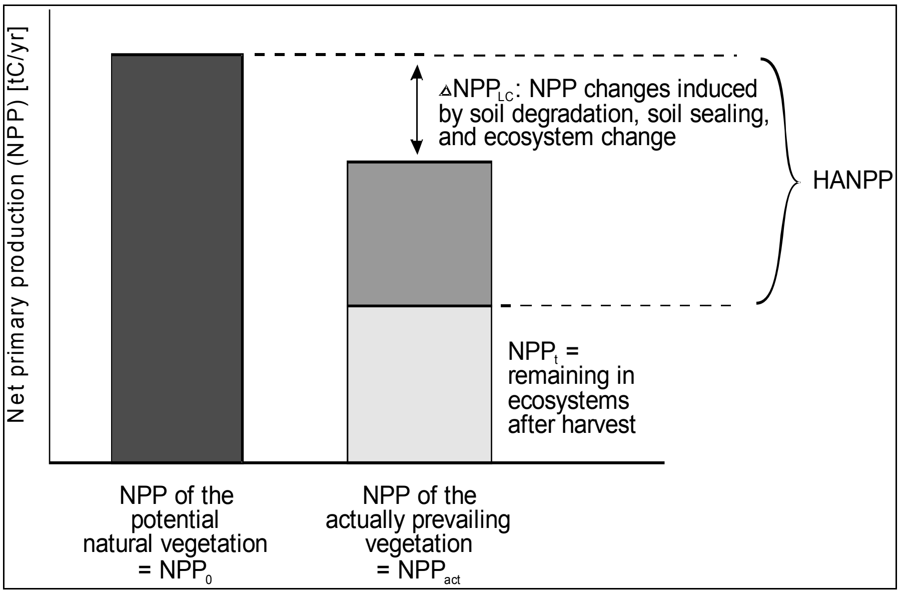

Figure 1. Definition of HANPP proposed by the authors. Sources: See text.

We have proposed a definition of HANPP (Haberl, 1997) that has proven its usefulness in spatially explicit (Haberl et al., 2001) as well as long-term (Krausmann, 2001) studies on a national scale. This definition (Figure 1) is related to Wright's (1990) suggestion and defines HANPP as the difference between the amount of NPP that would be available in an ecosystem in the absence of human activities (NPP_0) and the amount of NPP which actually remains in the ecosystem, or in the ecosystem that replaced it under current management practices (NPP_t). NPP_t can be calculated by quantifying the NPP of the actual vegetation (NPP_{act}) and subtracting the amount of NPP harvested by humans (NPP_h). HANPP is then defined as NPP_0-NPP_t with $NPP_t = NPP_{act} – NPP_h$. If one denotes as ΔNPP_{LC} the difference between NPP_0 and NPP_{act}, HANPP becomes equal to $NPP_h+\Delta NPP_{LC}$.

This definition has the following advantages: (1) It avoids being too inclusive. Even in strongly human-impacted systems such as grasslands, managed forests, or even cropland, some of the NPP is used by wild-living organisms not controlled or used by humans, thus supporting some, in grasslands often even a very high, biodiversity. (2) It is robust in time-series calculations. Land use sometimes reduces NPP, even prevents it altogether (e.g. soil sealing), but technologies such as irrigation, fertilization or use of improved crop varieties may also raise NPP over its natural potential. Such effects are significant and historically variable, and should thus be included in any comprehensive HANPP assessment. For example, in Austria changes in agricultural technology increased aboveground productivity on agricultural land by a factor of 2.6 from 1830 to 1995 (Krausmann, 2001).

Some problems remain, however. For example, how should wood harvest be dealt with? Wood is accumulated in a forest over many years, so harvest is the product of NPP accumulated over a period longer than the current year. This may result in negative NPP_t values, even if averaged over larger regions, if stock-depleting forest management practices prevail. How should crop residues not actually harvested, but ploughed into the soil after harvest, be dealt with? In our studies on Austria we chose to include them as „appropriated," because these studies focused on the aboveground compartment, and the biomass was clearly removed from that compartment. Other definitions may be more useful under different circumstances. Biomass returned to the ecosystem on-site (e.g. dung excreted by grazing animals) might also be included in a definition of HANPP. Some authors have chosen to also include biomass killed during harvest (e.g. roots) in their HANPP definition (O'Neill et al., 2006, see also Imhoff et al., 2004). A final weakness is that in some ecosystems the notion of a natural NPP in the absence of human activity may be questionable; NPP is variable on the timescale of decades and will be influenced by variations in climate, grazing and nutrient conditions. Human influence (e.g. regular burning of praries) may also reach back thousands of years.

In any case, it is important that HANPP studies be explicit in their definitions as to which biomass flow was or was not included in the definition of harvest used. We argue that a minimum requirement for any indicator to be called HANPP is that it (1) refers to a defined area of land, not to the biomass or NPP consumed by a defined population, (2) comprises an assessment of ΔNPP_{LC} and NPP_h, (3) avoids being too inclusive, while not being restricted only to biomass directly used by humans.

3. Some basics of HANPP methodology

In order to be able to calculate HANPP it is necessary to assess three properties: (1) NPP_0, i.e. the NPP of the vegetation that would be assumed to prevail in the absence of human land use (potential vegetation; Tüxen, 1956), (2) NPP_{act}, i.e. the NPP of the currently prevailing vegetation and (3) NPP_h, i.e. the human harvest of NPP. Different methods are available to estimate these three properties. Which one is most appropriate depends on the scope and purpose of the study. One of the strengths of HANPP is that it can be assessed in a spatially explicit way, i.e. it is possible to produce maps of HANPP that localize the human impact on ecosystems. In this case, the three above-mentioned parameters must be calculated in a spatially explicit way, using geographic information systems (GIS) technology (e.g., Haberl et al., 2001).

The most important factors influencing NPP in the absence of human activities are climate (above all, temperature and precipitation) and soil quality. Numerous models, so called Dynamic Global Vegetation Models, DGVMs, exist that can be used to calculate NPP_0 on a global level (Cramer et al., 1999). These models are spatially explicit and can mostly be used at a resolution of 0.5° (c. 50x50 km at the equator; e.g. Sitch et al., 2003). Similar models are available that can be used for smaller spatial scales. An alternative method is to extrapolate typical values of NPP per unit area and year from the literature (e.g., Ajtay et al., 1979, Cannell, 1982, Lieth and Whittaker, 1975) or to use simple models such as Lieth's "Miami model" that only requires data on mean annual temperature and precipitation (Lieth, 1975). While the credibility of the latter two simple approaches might be limited, a cross-check of DGVM results with data from the literature on the NPP of potential vegetation can be useful. Spatially explicit studies require gridded (GIS) data on potential vegetation, soil and climate. Credible results will require the availability of a suitable ecosystem model capable of reliably calculating NPP at the spatial resolution needed for the particular study.

Several methods are available to assess the NPP of the currently prevailing vegetation. In any case, the availability of a reliable dataset on land use and land cover is essential. A spatially explicit HANPP assessment it obviously only possible if spatially explicit (i.e. gridded) land-use and land-cover data are available in a GIS database. In order to be able to make use of data from agricultural and forestry statistics as well as forest inventories – indispensible sources of any HANPP calculation – it is required that cropland area in this dataset be consistent with cropland areas recorded in the specific agricultural statistics that should be used; the same holds for forestry. Availability of reliable data consistent with statistical sources on urban areas, wilderness and grazing land is often a major challenge for spatially explicit HANPP studies.

For cropland, the most reliable method is to use harvest indices (Evans, 1993; Loomis and Gerakis, 1975, Loomis, 1983, Wirsenius, 2000; Wirsenius, 2003) that extrapolate total NPP from the amount of crop harvested according to agricultural statistics (e.g FAO, 2005a). For managed forests, most HANPP studies conducted so far used the assumption that their NPP were equal to that of unmanaged forests (e.g., Haberl et al., 2001). This assumption may be questionable, as some authors have argued that forest management would greatly increase NPP because it would favour younger, more productive stages in forest succession – but other authors have made exactly the opposite claim, arguing that forestry often results in degradation of forest ecosystems. For alternative approaches see O'Neill et al. (2006). For areas with little or no human use the assumption $NPP_0 = NPP_{act}$ is obviously plausible. Built-up land is commonly assumed to be devoid of NPP ($NPP_{act} = 0$), but it is important to note that data on urban land usually include areas covered by vegetation such as parks, gardens or vegetation along roads. These areas are often irrigated and therefore quite productive which must of course be taken into account.

Grazing land is the most challenging item to be considered in calculating NPP_{act}. First, data on the area covered with different kinds of grazing land (meadows mowed with different intensities, pastures with different grazing intensities, rangelands and other grazed ecosystems) are mostly of poor quality and often unreliable due to their low economic value and to the existing ambiguities in definitions (Lambin and Geist, 2006). Second, the effect of grazing and mowing on the productivity of grasslands and grazed ecosystems in general is also not well understood and documented. Case studies show that grazing may both enhance ("compensatory growth") or reduce productivity ("degradation"), depending on its intensity and a host of other factors such as precipitation or soil quality. Moreover, the effect of land clearing (removal of forests) for pastures or grazing land on NPP is also not documented.

Assessing biomass harvest may also be less straightforward than one might think. Data on crop and timber harvest are usually readily available from statistical sources (e.g FAO 2002, 2004, 2005a). These are quite reliable for crops but often less so for harvest in forests, especially due to underreporting of illegal logging in the tropics and subsistence woodfuel gathering. For forests it is also important to note that wood harvest is actually not taken from the NPP of the current year but is a stock accumulated in the past decades or even centuries. This may in theory even result in negative NPP_t values if the above-mentioned formulae are applied, but this can usually be avoided by using averages of forest growth and wood harvest over larger regions. A similar problem may occur in regions with strong net forest losses.

The most difficult part of any assessment of NPP_h is the estimation of NPP harvested on grazing land (i.e. biomass grazed by livestock or hay mowed) because these flows are usually not recorded in agricultural statistics. This biomass flow can be estimated by calculating the so-called "grazing gap;" that is, the amount of roughage required to feed the existing stock of ruminants after market feed has been taken into account. A useful approach in that context is the use of livestock feed balances based on data on livestock numbers and livestock production from agricultural statistics (e.g., Wirsenius 2000, 2003). The result of such a calculation can be cross-checked with the productivity of grazing land calculated in the above-discussed steps.

As data on belowground NPP are considerably more uncertain than those on aboveground NPP many HANPP studies were restricted to the aboveground compartment. In any case, it seems highly desirable to account for aboveground and belowground processes separately. More detailed information on HANPP methods can be found in the literature (e.g., Haberl et al., 2001, Haberl, 2002).

4. Global HANPP – an overview

Biomass flows can be expressed in terms of flows of dry matter biomass (kg/yr), in terms of energy (J/yr, usually expressed as Gross Calorific Value = Upper Heating Value) or in terms of carbon flows (kg C/yr). In order to facilitate comparison of the global results reviewed below we converted all results to Pg C/yr (1 Pg = 10^{15} g = 10^{9} t = 1 Gt = 1 billion tons), using the following conversion factors: 1 kg dry matter biomass = 0.5 kg C and 1 kg dry matter biomass = 18.5 MJ.

As early as 1973 Whittaker and Lieth (1973) reported that humans harvested 1.6 Pg C/yr from terrestrial ecosystems as food and wood in the 1950s, a flow of biomass that amounted to only 3% of their estimate of total global terrestrial NPP (54 Pg C/yr). This finding (Table 1) hardly raised concerns, but this changed rapidly with the publication of the famous study by Vitousek and colleagues (1986) that reported the following result: "We estimate that organic material equivalent to about 40% of the present net primary production in terrestrial ecosystems is being co-opted by human beings each year. People use this material directly or indirectly, it flows to different consumers and decomposers than it otherwise would, or it is lost because of human-caused changes in land use. People and the associated organisms use this organic material largely, but not entirely, at human direction, and the vast majority of other species must subsist on the remainder." (Vitousek et al., 1986, p. 372). Wright`s (1990) study was a recalculation of the study by Vitousek and colleagues that used more recent data sources and a different definition (see above); differences in definitions explain a much larger proportion of the differences in the result than the use of more recent data.

A more recent probabilistic study (Rojstaczer et al., 2001) that adopted Vitousek et al.'s intermediate definition and was based on Monte-Carlo techniques reported an alarmingly large uncertainty of global HANPP, a conclusion that was criticized by other authors (e.g. Field, 2001, Haberl et al., 2002). Using again another definition (outlined above), Imhoff and others (2004) arrived at an estimate of global human consumption of NPP of 14.7 Pg C/yr or 20% of terrestrial NPP. A recent study of the authors (Haberl et al., 2006a, Erb et al., 2005) based on extensive use of spatially explicit (gridded) data reported a global HANPP value of 14.7 Pg C/yr or 22% of total terrestrial NPP. These are the only available data on the global level that are (1) compatible with the HANPP definition outlined in Figure 1, (2) based on country-level data on land use, livestock grazing, forestry, urban areas, and so on, (3) include biomass consumed in human-induced fires and (4) are available in a 5min (10x10 km) geographic grid. For the aboveground compartment, this study reported a considerably higher HANPP of almost 30%. A recalculation of HANPP according to the definition used by Vitousek et al. (1986), but using the far more detailed database available for that latter study, confirmed that differences resulting from the use of different definitions were by far larger than differences resulting from uncertainties in the data.

Table 1. Overview of estimates of global HANPP given by different authors.

Study	Reference time	HANPP absolute* [Pg C/yr]	HANPP relative* [%]**
Whittaker and Lieth (1973)	1950s	1.6	3%
Vitousek et al. (1986) low	1970s	2.6	3%
Vitousek et al. (1986) intermediate	1970s	20.3	27%
Vitousek et al. (1986) high	1970s	29.5	39%
Wright (1990)	1970s-1980s	17.7	24%
Rojstaczer et al. (2001)	1980s-1990s	19.5±14	32% (10-55%)
Imhoff et al. (2004)	1995	11.5 (8.0-14.8)	20% (14-26%)
Haberl et al. (2006a)	2000	14.7	22%

* Note the differences in definitions used in each study discussed in the text.

** Per cent of actual or potential NPP. Note that estimates of NPP_{act} and NPP_0 also vary considerably; for example Whittaker and Lieth's value of NPP_{act} (54 Pg C/yr) was much lower than Vitousek et al's estimate (66 Pg C/yr). The current "best guess" of NPP_0 is 66 Pg C/yr and that of NPP_{act} 59 Pg C/yr (Haberl et al., 2006a, Erb et al., 2005).

5. Outlook – the meaning and significance of HANPP

HANPP is definitely useful as a measure of the physical size of the economy relative to the containing ecosystem (Daly, 2006, p.1): It demonstrates how much of the trophic energy that would be available for wild-living animals and other heterotroph organisms in the absence of human activities is still in place. As such, it is an extremely valuable indicator of the "human domination of ecosystems" on the global scale (Vitousek et al., 1997) and of the intensity of socio-economic "colonization of ecosystems" (Fischer-Kowalski and Haberl, 1997, Haberl et al., 2004a).

Studies of global HANPP gained attention in the literature on sustainable development because HANPP was often interpreted as an indicator for ecological limits to growth (Meadows et al., 1992, Sagoff, 1995, Costanza et al., 1998). This notion has meanwhile lost credit, however, because (a) economic growth may proceed even without growing biomass use (Haberl et al., 2006b) and (b) long-term studies of HANPP have shown that HANPP may decline during industrialization if biomass harvest grows due to agricultural intensification rather than due to an extension of farmed areas (Davidson, 2000, Haberl et al., 2001, Krausmann, 2001).

An obvious implication of HANPP is that growth in the amount of biomass used by humans for their socio-economic metabolism must be envisaged with caution. In particular, caveats are warrented with respect to policies aiming to promote the use of biomass as a source of technical energy as well as raw material (Allgeier et al., 1995, European Commission, 1997, Sampaio-Nunes, 1995). Biomass already plays a significant role in global socio-economic energy supply. Biomass currently contributes some 9-13%, that is 35-55 EJ/yr (1 EJ = 10^{18} Joule), to the global supply of technical energy (see Table 2). This figure, however, by far underestimates the importance of biomass for humanity's "energetic metabolism" (Haberl, 2001a, Haberl, 2001b): Global human biomass harvest, including crops, by-products, grazing by livestock, fibre consumption and forest products amounted to about 235 EJ/yr around 1993 (Table 2). This value includes an estimate of biomass used in subsistence economies for energy provision (Hall et al., 1993a, Scurlock and Hall, 1990) unaccounted for in statistical data such as those of the FAO (FAO, 2002)

Notable future increases in biomass demand are expected. The projected growth of world population to 7.5-8.5 billion in 2030 and 7-11 billion in 2050 (Lutz et al., 2004) together with likely improvements in human diets are strong driving forces for further increases in the amount of biomass required as food and feed. Moreover, many energy scenarios also predict strong increases in the amount of biomass used for energy provision (Table 2). Further growth of biomass energy use might not only result in increased competition between food and energy supply, but also in further increases in HANPP with possible adverse ecological effects.

Table 2. Current and projected future level of global biomass and energy use and global terrestrial net primary production: A compilation of estimates.

	Energy flow [EJ/yr]	Year	Sources
1. Current global use of energy and biomass			
Biomass used for the provision of technical energy	35-55	mid 1990s	[1,2,3,4]
Global technical energy consumption excluding biomass	350 (376)	1995	[5]
Global human biomass extraction (wood, food feed, etc.)	235	1992-94	[6]
2. Scenarios of future use / biomass potentials			
Short-term potential according to *WEA*	145	2025	[2]
Mid-term potential according to *WEA*	94-280	c2050	[2]
Long-term potential according to *WEA*	132-325	2100	[2]
Range of mid-term potentials/scenarios found in a review	35-450	2050	[1]
WEC/IIASA scenarios mid-term	78-154	2050	[3]
WEC/IIASA scenarios long-term	174-266	2100	[3]
IPCC-SRES scenarios mid-term	52-193	2050	[7]
IPCC-SRES scenarios long-term	67-376	2100	[7]
Potential according to Fischer/Schrattenholzer	370-450	2050	[8]
Potential according to Hoogwijk et al.	33-1135	2050	[9]
3. Global terrestrial NPP			
Average from PIK model comparison project	2 140	mid 1990s	[10]
NPP estimate by Ajtay et al. (1979)	2 460	1970s	[11]
Current „best guess“ according to Saugier et al.(2001)	2 440	mid 1990s	[12]

[1] Berndes et al., 2003 (summarizes findings of 17 studies, including some of the below-quoted).
[2] Turkenburg, 2000.
[3] Nakicenovic et al., 1998.
[4] Hall et al., 1993b.
[5] Podobnik, 1999, own conversion assuming 1 toe = 41.868 GJ (net calorific value). Value in brackets: estimate of gross calorific value.
[6] Haberl et al., 2006b. This estimate is based on FAO data for wood harvest, data for agricultural biomass harvest, including grazing, assessed by Wirsenius, 2000, an estimate of fibre consumption, and an estimate on the under-representation in FAO statistics of biomass used for energy provision in subsistence economies.
[7] Nakicenovic and Swart, 2000.
[8] Fischer and Schrattenholzer, 2001.
[9] Hoogwijk et al., 2003.
[10] Cramer et al., 1999, converted assuming a carbon content of biomass of 47.5% and 18.5 MJ/kg gross calorific value of dry matter biomass.
[11] Ajtay et al., 1979, converted assuming 18.5 MJ/kg gross calorific value of dry matter biomass.
[12] Saugier et al., 2001, converted as in [10].

Policies aimed at promoting the use of biomass for energy provision should therefore aim at the highest possible efficiency in biomass use. The utilization of biomass from residues (i.e., agricultural crop residues, forest residues, manure, organic wastes) should be given priority over biomass utilization schemes that require the additional harvest of biomass. There exist considerable potentials for such a strategy of „cascade utilization of biomass“ (Fraanje, 1997, Haberl and Geissler, 2000, Haberl et al., 2003, Lal 2004). On a global level, biomass residues could yield some 30-112 EJ/yr (Haberl and Erb, 2006).

Moreover, empirical studies increasingly demonstrate that HANPP is a major indicator of human pressures on ecosystems and may have adverse effects on biodiversity. On an abstract level it is obvious why HANPP is ecologically relevant: NPP is a central parameter of ecosystem functioning (Lindemann, 1942, Whittaker and Likens, 1973), human-induced changes of NPP thus affect patterns, processes and functions of ecosystems almost by definition. HANPP is directly associated to the provision of ecosystem services (Millenium Ecosystem Assessment, 2005, Daily et al., 1999), such as the provision of biomass through agriculture and forestry. But land-use induced changes in productivity (ΔNPP_{LC}) may also affect many important ecosystem services such as the resilience, buffering capacity or the absorption capacity for wastes and emissions.

HANPP alters energy flows within food webs (Field, 2001). Based on the species-energy hypothesis (Gaston, 2000), HANPP has been hypothesized to contribute to biodiversity loss (Haberl, 1997, Wright, 1990). Only few empirical studies have been conducted so far to probe this idea, however. These studies have generated evidence in support of the HANPP-biodiversity hypothesis (Haberl et al., 2004b, Haberl et al., 2005), but further evidence referring to a wider range of ecosystems seems desirable. HANPP is relevant in the context of global water flows (Gerten et al., 2005), carbon flows (DeFries et al., 1999, McGuire et al., 2001) and – as biomass contains nitrogen (N), and N fertilizer is an important factor for agricultural productivity – N flows.

HANPP relates to important global sustainability issues such as endemic malnourishment of a large proportion of 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, FAO, 2004) with detrimental consequences for biodiversity (Heywood and Watson, 1995, Loreau) and global, human-induced alterations of biogeochemical cycles (Crutzen and Steffen, 2003, Steffen et al., 2004).

We conclude that the analysis of socio-economic drivers of HANPP as well as of its ecological impacts should remain high on the agenda of sustainability science. In particular, understanding the interrelations between HANPP and changes in economic structures and processes, especially those related to transitions from agrarian to industrial society, should be a priority of Ecological Economics.

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