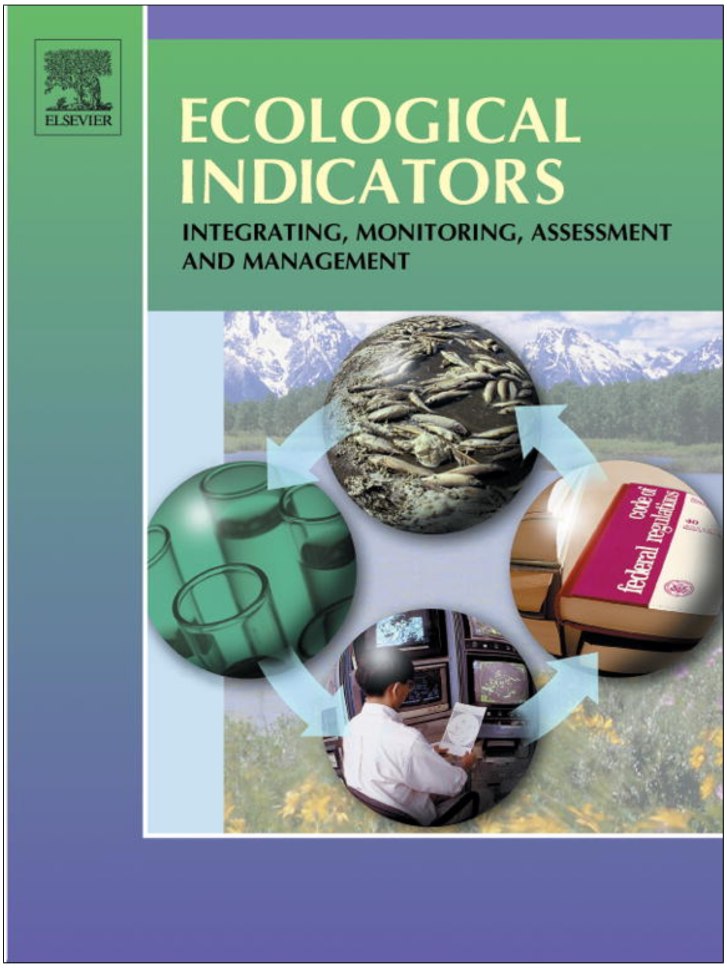
ELSEVIER
ECOLOGICAL INDICATORS
INTEGRATING, MONITORING, ASSESSMENT AND MANAGEMENT

Ecological Indicators 23 (2012) 222–231

Contents lists available at SciVerse ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Natural and socioeconomic determinants of the embodied human appropriation of net primary production and its relation to other resource use indicators

Helmut Haberl[a,*], Julia K. Steinberger[a,b], Christoph Plutzar[a], Karl-Heinz Erb[a], Veronika Gaube[a], Simone Gingrich[a], Fridolin Krausmann[a]

[a] *Institute of Social Ecology Vienna, Alpen-Adria Universitaet Klagenfurt, Wien, Graz, Schottenfeldgasse 29, 1070 Vienna, Austria*
[b] *Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*

ARTICLE INFO

Article history:
Received 1 December 2011
Received in revised form 20 March 2012
Accepted 23 March 2012

Keywords:
Human appropriation of net primary production (HANPP)
Embodied HANPP (eHANPP)
CO_2 emissions
Ecological footprint
Cross-country analysis
Socioeconomic metabolism

ABSTRACT

Indicators of resource use such as material and energy flow accounts, emission data and the ecological footprint inform societies about their performance by evaluating resource use efficiency and the effectiveness of sustainability policies. The human appropriation of net primary production (HANPP) is an indicator of land-use intensity on each nation's territory used in research as well as in environmental reports. 'Embodied HANPP' (eHANPP) measures the HANPP anywhere on earth resulting from a nation's domestic biomass consumption. The objectives of this article are (i) to study the relation between eHANPP and other resource use indicators and (ii) to analyse socioeconomic and natural determinants of global eHANPP patterns in the year 2000. We discuss a statistical analysis of >140 countries aiming to better understand these relationships. We found that indicators of material and energy throughput, fossil-energy related CO_2 emissions as well as the ecological footprint are highly correlated with each other as well as with GDP, while eHANPP is neither correlated with other resource use indicators nor with GDP, despite a strong correlation between final biomass consumption and GDP. This can be explained by improvements in agricultural efficiency associated with GDP growth. Only about half of the variation in eHANPP can be explained by differences in national land-use systems, suggesting a considerable influence of trade on eHANPP patterns. eHANPP related with biomass trade can largely be explained by differences in natural endowment, in particular the availability of productive area. We conclude that eHANPP can deliver important complimentary information to indicators that primarily monitor socioeconomic metabolism.

1. Introduction

Human activities are altering the biosphere at an increasing pace. They have already changed the earth system to an extent that is large enough to motivate prominent scholars to introduce a new geological epoch, the 'anthropocene' (Crutzen and Steffen, 2003; Steffen et al., 2007). Serious environmental concerns include anthropogenic climate change as well as the rapid loss of biodiversity and valuable ecosystems (IPCC, 2007; Millennium Ecosystem Assessment, 2005). Far-reaching changes in the human use of biophysical resources such as energy, materials, land, etc., are needed in order to slow down these processes (Fischer-Kowalski and Haberl, 2007; IPCC, 2007; WBGU, 2011).

Moving towards more sustainable patterns of resource use will require data and analysis to better understand the interrelations between extraction and consumption of resources, economic prosperity and societal well-being. The socioeconomic metabolism approach has been useful in constructing resource use indicators (e.g., Ayres and Simonis, 1994; Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998; Krausmann et al., 2009a; Martinez-Alier, 1987). Material and energy flow indicators generally measure society's input and use of biophysical resources at local (including urban), regional, national or global levels as well as outputs such as wastes and emissions. Several aspects of resource flows can be observed: 'Material flow analysis' accounts for bulk flows of chemically diverse groups of materials (e.g., biomass, fossil fuels or mineral resources), 'substance flow analysis' considers flows of substances such as carbon, nitrogen or metals, whereas 'energy flow analysis' is focused on energy (e.g., Erb et al., 2008;

Abbreviations: DEC, domestic energy consumption; DMC, domestic material consumption; ΔNPP_{LC}, change in NPP resulting from land conversion (defined as $NPP_0 - NPP_{act}$); GDP, gross domestic product; EF, ecological footprint; eHANPP, embodied HANPP; HANPP, human appropriation of net primary production; NPP, net primary production, i.e. the yearly biomass production of plants; NPP_0, NPP of potential natural (=undisturbed) vegetation; NPP_{act}, NPP of the currently prevailing vegetation; NPP_h, NPP harvested or destroyed during harvest; NPP_t, NPP remaining in the ecosystem after harvest; TPES, total primary energy supply.

[*] Corresponding author. Tel.: +43 1 5224000 406; fax: +43 1 5224000 477.
E-mail address: helmut.haberl@aau.at (H. Haberl).

1470-160X/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ecolind.2012.03.027

Graedel and Cao, 2010; Haberl et al., 2006; OECD, 2008; Weisz et al., 2006).

Material and energy flow accounts need to be complemented by indicators of land use, which is one of the most important human drivers of change in the biosphere (Foley et al., 2005; Turner et al., 2007). Land is used for the supply of food, feed, fibres and energy, for the absorption of wastes and for buffering services, e.g. water retention or protection from avalanches, as well as for buildings and other infrastructures (Dunlap and Catton, 2002). In this article, we consider land use with two related, but different indicators: (1) the human appropriation of net primary production (HANPP) and (2) the ecological footprint (Haberl et al., 2004b; Wackernagel et al., 2002).

Compared to the large body of research on material and energy flow indicators (Ayres and Simonis, 1994; Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998; Graedel and Cao, 2010; Haberl et al., 2006; Hak et al., 2012; Krausmann et al., 2009a; Martinez-Alier, 1987; OECD, 2008; Weisz et al., 2006) and on the ecological footprint (Wackernagel et al., 2002; Bastianoni, 2012), HANPP has so far received relatively little attention. In this article, we focus on two distinct definitions of HANPP: (1) HANPP on national territory and (2) HANPP related to a nation's apparent consumption of food, feed, fibre and bioenergy, denoted as 'embodied HANPP' (abbreviated 'eHANPP'). While socioeconomic and natural determinants of HANPP (Krausmann et al., 2009b) and its relation to other biophysical indicators (Erb et al., 2009a; Haberl et al., 2004b) have recently been studied, a similar analysis for eHANPP is missing.

Hence, the objectives of this paper are twofold:

(1) To analyse the relation of eHANPP to other resource use indicators, in particular to HANPP, the ecological footprint as well as a suite of indicators of socioeconomic material and energy use.
(2) To analyse the natural as well as socioeconomic determinants of global patterns in eHANPP at the national level.

The article is based on existing data with a global coverage that refer to the year 2000. It aims to contribute to discussions on resource use efficiency, sustainability policies as well as the design of indicator systems to measure the use of resources.

2. Methods and data

2.1. The concepts of HANPP and embodied HANPP

The human appropriation of net primary production (HANPP) is an integrated socio-ecological indicator of the intensity of human use of terrestrial ecosystems. It has been used in scientific research (Erb et al., 2009a; Haberl, 1997; Haberl et al., 2007; Vitousek et al., 1986; Whittaker and Likens, 1973; Wright, 1990) as well as in environmental reporting (EEA, 2010). HANPP served as a measure of 'human domination' of ecosystems (Vitousek et al., 1997) and as a measure of resource use and strong sustainability (Haberl, 1997; Costanza, 1991). It has been applied in evaluating bioenergy potentials (Haberl et al., 2011). Moreover, previous empirical analyses have shown that HANPP is a valid indicator of socioeconomic pressures on ecosystems and biodiversity (Haberl et al., 2004a, 2005; Wright, 1990). As this paper is based on a re-analysis of previously published HANPP datasets, we only give a short summary of HANPP methods required for correctly interpreting HANPP results. Details on HANPP methods can be found elsewhere (Haberl et al., 2007).

Net primary production (NPP) is the process in which green plants produce biomass through photosynthesis. NPP is the total amount of energy available for ecological food webs and reproduction of biological biomass stocks, i.e. the standing biomass of plants, soil organic carbon, etc. HANPP is the sum of (1) changes in NPP resulting from land conversion (ΔNPP_{LC}) and (2) human withdrawal of NPP from ecosystems through harvest, including parts of plants killed during harvest, livestock grazing, fires, etc. HANPP is calculated in the following steps: first, NPP_0 – the NPP of the vegetation that would exist in the absence of land use under current climate conditions – is assessed with vegetation models. Second, the effect of land use on NPP (ΔNPP_{LC}) and the amount of NPP harvested (NPP_h) are derived from land use data from remote sensing, NPP modelling as well as from statistical data (for detail see Haberl et al., 2007).

According to this definition, national HANPP refers to changes in the availability of NPP in the ecosystems on a country's territory (Haberl et al., 2007). HANPP thereby provides information on the intensity of land use within a country which is important in many contexts. However, it does not consider land used outside a country's borders to produce imported goods. Also, the share of the HANPP on national territory related to the production of exported goods is not subtracted. In short, HANPP relates to the effects of land use within a country's borders but does not consider trade.

The concept of 'embodied HANPP' (eHANPP) is a measure of the HANPP related to the production of goods consumed within a country (Erb et al., 2009a,b; Haberl et al., 2009). The difference between a country's HANPP and its eHANPP stems from trade: eHANPP is derived from HANPP by adding the HANPP related to imported products and subtracting that related to exported products (Erb et al., 2009b). Based on population density data, the HANPP embodied in the consumption of biomass-based products can be mapped (Imhoff et al., 2004). The difference between HANPP and embodied HANPP of each pixel indicates the 'spatial disconnect' between production and consumption (Erb et al., 2009b). Embodied HANPP (Fig. 1) is related to the concept of 'apparent consumption' (domestic extraction plus imports minus exports) underlying many other biophysical resource indicators: domestic material consumption (DMC), domestic energy consumption (DEC), total primary energy supply (TPES) and the ecological footprint are all based on this general concept, despite the different metrics (Joule, kg, global hectares) as well as system boundaries used in calculating them.

Conceptually, eHANPP is an approach that can be used to account for environmental pressures related to trade and consumption, akin to approaches such as 'virtual water' or 'water footprints' (Hoekstra and Hung, 2005; Gerbens-Leenes et al., 2009) and 'carbon footprints' or 'embodied CO_2 emissions' (Larsen and Hertwich, 2010; Peters and Hertwich, 2008; Wiedmann, 2009).

2.2. Data sources

This study is based on data from previous publications and publicly available statistical sources summarized in Table 1. Data on eHANPP related to each country's biomass metabolism were taken from Erb et al. (2009b). These data only consider the eHANPP resulting from the production of biomass-based products such as food, paper or wood, but not the eHANPP related to other products. For example, biomass use in the production chain of manufactured products such as cars was not considered. eHANPP was calculated based on trade statistics separately for agricultural and forestry products.

In addition, data were taken from official international bodies such as the FAO, UNEP, the IEA and the World Bank (see Table 1). Most datasets include approximately 140 countries which usually cover >90% of the earth's terrestrial surface (except Greenland and Antarctica) and are inhabited by >90% of world population. We used standard least-square regression techniques to analyse statistical relations between the different indicators. We proceeded in a hypothesis-based exploratory fashion, thereby taking into account previous attempts to analyse determinants of HANPP, eHANPP and other biophysical resource use indicators (Krausmann et al., 2009b;

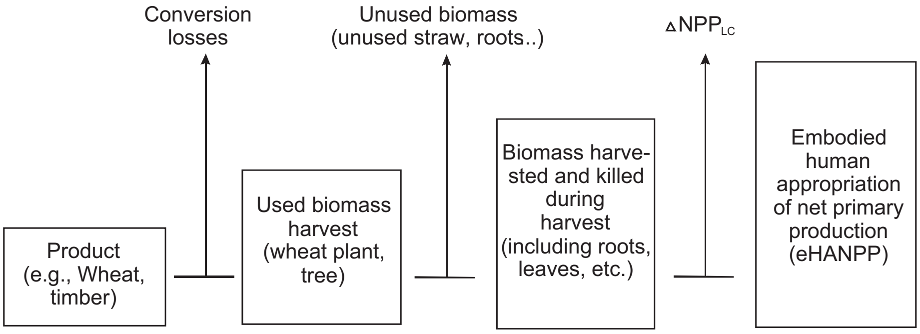

Fig. 1. The concept of embodied HANPP (eHANPP) considers conversion losses, by-product flows (such as unused straw or residues – if they are used they are included in used biomass harvest) and productivity changes resulting from agriculture and forestry.

Source: redrawn after Haberl et al. (2009).

Steinberger et al., 2010; Steinberger and Roberts, 2010; Steinberger and Krausmann, 2011).

3. Results and discussion

3.1. eHANPP and other biophysical resource use indicators

In order to explore the significance of eHANPP in the overall context of biophysical resource use indicators, we performed ordinary least square regressions between eHANPP and other resource use indicators. In order to eliminate effects due to country size, all indicators were expressed as yearly flows per capita. The hypotheses to be tested were (1) that resource use grows with growing GDP and, hence, (2) all biophysical resource indicators should be correlated among each others, despite the fact that they focus on different aspects of resource use and are measured in different units.

The correlations are shown in Table 2 for ≥122 countries with data for all indicators, representing >93% of the global population. eHANPP (column 1) is most closely correlated to HANPP on national territory, but the effect of trade is still considerable: variations in HANPP on national territory explain less than half of the variations in eHANPP ($R^2 = 0.48$). eHANPP is also poorly correlated to biomass consumption (biomass DMC) ($R^2 = 0.34$), and not correlated to the ecological footprint (EF). There is no correlation between eHANPP and CO_2 emissions from fossil fuel combustion and cement manufacture (CO_2 emissions from land-use change are not included), a weak correlation of eHANPP with total primary energy supply (TPES), which includes biomass used for heating and cooking, and with domestic energy consumption (DEC) and domestic material consumption (DMC). DEC includes not only technical energy use, but also biomass used for food, feed, etc. (Haberl, 2001). The above-formulated hypotheses are thus rejected, motivating a search for more appropriate explanations which is undertaken in the following paragraphs.

The absence of strong correlations between eHANPP, TPES and CO_2 emissions can be explained by conceptualizing industrialization as a process of 'emancipation' from land-based resources, in particular biomass, as society's main energy source (Boyden, 1992; Fischer-Kowalski and Haberl, 2007; Martinez-Alier, 1987). Long-term studies of socioeconomic metabolism have shown that the transition from a biomass-based energy system to fossil fuels and, quantitatively less important, to nuclear energy and large-scale hydropower, was a major driver of economic growth during industrialization (Krausmann et al., 2009a; Sieferle et al., 2006).

eHANPP, HANPP and the domestic material consumption (DMC) of biomass are not or at best poorly correlated with CO_2, TPES, total DMC and DEC. This confirms the notions that (1) the process of development is based primarily on a growth of the use of fossil energy and mineral resources (Krausmann et al., 2009a; Steinberger et al., 2010) and (2) current changes in resource use in developing countries are similar to the historic agrarian–industrial transition in industrialized countries (Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2008b). The fraction of biomass is reduced in both material and energy supplies to industrial economies, although its absolute level may be constant or even increasing.

The poor correlation between eHANPP, DEC, DMC and the EF needs explanation because biomass flows are a major component of all these indicators; hence one would assume that they should be correlated. The EF includes cropland, grazing areas, fishing grounds, and forests required to procure products such as food, bio-energy, paper or construction materials but is also strongly influenced by the 'virtual area' required to hypothetically sequester CO_2 from fossil fuels (Wackernagel et al., 2002). Domestic material consumption (DMC) includes biomass from cropland, grazing areas, and forests as major components. Domestic energy consumption (DEC) was designed as an extension of conventional energy balances and indicators such as TPES to fully capture the relevance of biomass for a society's energy supply, including food and feed as well as animal and human labour, in a way that is compatible with DMC. The correlation of these indicators amongst each other can be seen in Table 2. The EF (column 5) is strongly correlated with CO_2 emissions, TPES, DEC and DMC ($R^2 > 0.74$ for all correlations). In contrast, the correlation between the EF, biomass DMC and HANPP as well as eHANPP is poor.

We interpret these results as follows: many biophysical resource use indicators analysed here account for a country's throughput of materials and energy. They focus on different aspects of resource use and are based on different units: mass in material flow analysis (DMC), energy in energy flow analyses (TPES, DEC), globally standardized bioproductive area ('global hectares') in the EF, and a major component of national 'domestic processed output' (DPO; see Matthews et al., 2000) in the case of CO_2 emissions. Although DMC, TPES, DEC, DPO and the EF are not identical due to differences in the composition of socioeconomic metabolism and different units, they are correlated, as hypothesized, because they represent different metrics to capture the same process, i.e. the throughput of materials and energy. The pattern differs for HANPP and eHANPP because they are related to effects of land use on ecosystems, i.e. another aspect of resource use. The system boundary relevant for HANPP and eHANPP is not entry into the economy, but the effect of resource use on ecosystems. The striking difference in the patterns resulting from this distinction in system boundary emphasizes the importance of considering human resource use both from the perspective of economies and the perspective of the environment.

Table 1
Variables analysed in this study and data sources. All data refer to the year 2000.

Dataset	Variables	Unit(s)	Source(s)
Climate and geography	Mean temperature	[°C]	Hijmans et al. (2005)
	Mean precipitation	[mm/yr]	Hijmans et al. (2005)
	Mean latitude	[degrees]	ESRI (2004)[a]
	Actual evapotranspiration (AET)	[mm/yr]	Ahn and Tateishi (1994)
	Mean humidity	[index]	Deichmann and Eklundh (1991)
	Territory (area)	[km^2]	FAO (2006a)
	Productive land area	[km^2]	Haberl et al. (2007)
	Cropland suitability (area-weighted mean)	[index]	Ramankutty et al. (2002)
Land use	Infrastructure area	[km^2]	Erb et al. (2007)
	Cropland area	[km^2]	Erb et al. (2007)
	Forestry area	[km^2]	Erb et al. (2007)
	Grazing land (classes 1–4)	[km^2]	Erb et al. (2007)
	Non-productive, snow	[km^2]	Erb et al. (2007)
	Wilderness	[km^2]	Erb et al. (2007)
Population	Population number	[1000 persons]	FAO (2006a)
	Urbanization	[%]	UN (2008)
	Agricultural population	[1000 persons]	FAO (2006a)
Agricultural indicators	Fertilizer use (NPK content)	[1000 t nutrient/yr]	FAO (2006a)
	Livestock (in livestock units)	[1000 LU][b]	Haberl et al. (2007)
	Non-market feed	[1000 t DM/yr][c]	Krausmann et al. (2008a)
	Market feed	[1000 t DM/yr]	Krausmann et al. (2008a)
	Livestock output	[1000 t DM/yr]	Krausmann et al. (2008a)
HANPP and biomass flow data	NPP_0 (for all land-use classes)[d]	[1000 t DM/yr]	Haberl et al. (2007)
	NPP_{act} (for all land-use classes)[e]	[1000 t DM/yr]	Haberl et al. (2007)
	NPP_h (harvest, by-flows, fires)	[1000 t DM/yr]	Haberl et al. (2007)
	HANPP	[1000 t DM/yr]	Haberl et al. (2007)
	HANPP%	[% of NPP_0]	Haberl et al. (2007)
	eHANPP	[1000 t DM/yr]	Erb et al. (2009b)
	Used extraction of biomass	[1000 t DM/yr]	Krausmann et al. (2008a)
	Domestic biomass consumption	[1000 t DM/yr]	Krausmann et al. (2008a)
	Final use of biomass	[1000 t DM/yr]	Krausmann et al. (2008a)
	Final use of plant biomass	[1000 t DM/yr]	Krausmann et al. (2008a)
	Final use of animal biomass	[1000 t DM/yr]	Erb et al. (2009b)
	Final use of other biomass	[1000 t DM/yr]	Erb et al. (2009b)
	Final use total non-energy	[1000 t DM/yr]	Erb et al. (2009b)
	Biomass for energy	[1000 t DM/yr]	Erb et al. (2009b)
	Fuelwood	[1000 t DM/yr]	Krausmann et al. (2008a)
	Biomass export plants	[1000 t DM/yr]	Krausmann et al. (2008a)
	Biomass export animals	[1000 t DM/yr]	Krausmann et al. (2008a)
	Biomass import plants	[1000 t DM/yr]	Krausmann et al. (2008a)
	Biomass import animals	[1000 t DM/yr]	Krausmann et al. (2008a)
	Wood imports	[1000 t DM/yr]	Krausmann et al. (2008a)
	NPP burned, anthrop. Fires	[1000 t DM/yr]	Lauk and Erb (2009)
	Burned areas	[km^2/yr]	Lauk and Erb (2009)
Socioeconomic indicators	Gross domestic product (GDP)	[10^9 US$] PPP 2000[f]	The World Bank Group (2007)
	Agricultural GDP [percent]	[%]	The World Bank Group (2007)
	Literacy rate	[%]	UNEP (2007)
	Life expectancy	[yr]	UNEP (2007)
	Gross enrollment ratio	[%]	UNEP (2007)
	HDI	[index]	UNEP (2007)
Biophysical resource use indicators	Ecological footprint	[gha/cap/yr]	www.globalfootprintnetwork.org
	Total primary energy supply	[ktoe/yr]	IEA (2007a,b)
	Share of biomass in TPES[g]	[%]	IEA (2007a,b)
	Domestic energy consumption	[GJ/cap/yr]	Krausmann et al. (2008a)
	Share of animal products in diet	[%]	Krausmann et al. (2008a)
	Carbon emissions per capita	[tC/cap/yr]	CDIAC (2007)
	Domestic materials consumption	[1000 t/yr]	Steinberger et al. (2010)

[a] Centroids calculated based on polygons provided by ESRI.
[b] LU: livestock units.
[c] DM: dry matter (mass of biomass with 0% water content).
[d] NPP of potential natural vegetation (hypothetical vegetation without human land use).
[e] NPP of currently prevailing vegetation.
[f] Purchasing power parity, US$ values referring to the year 2000.
[g] TPES: total primary energy supply.

3.2. Socioeconomic and natural determinants of national eHANPP

HANPP and eHANPP are related to the human use of the productive capacity of ecosystems. In order to better understand this crucial aspect of resource use, we analyse natural as well as socioeconomic determinants of eHANPP according to the conceptual model outlined in Fig. 2.

By definition, national HANPP and biomass trade co-determine the eHANPP of each country (Erb et al., 2009b). National HANPP depends on the national land-use system, i.e. the level of

Table 2
Coefficient of determination (R^2) for correlations between per-capita environmental indicators. All correlations are with logged values, for $N \geq 122$ countries representing >93% of the world's population. All correlations $R^2 > 0.1$ are significant at $p < 0.001$; correlations with $R^2 < 0.1$ are not shown.

		eHANPP	HANPP	Biomass DMC	Final biomass consum.	Ecolog. footprint	Domestic energy consum.	TPES	Carbon emissions	Total DMC	GDP
Embodied HANPP	t/cap/yr	–	0.48	0.34	0.11		0.14	0.11		0.15	
HANPP on national territory	t/cap/yr	0.48	–	0.46							
Biomass DMC	t/cap/yr	0.34	0.46	–	0.18	0.11	0.21			0.24	
Final biomass consumption	t/cap/yr	0.11		0.18	–	0.73	0.64	0.62	0.48	0.58	0.75
Ecological footprint	ha/cap			0.11	0.73	–	0.82	0.89	0.75	0.75	0.79
Domestic energy consumption	GJ/cap/yr	0.14		0.21	0.64	0.82	–	0.86	0.63	0.80	0.69
Total primary energy (TPES)	GJ/cap/yr	0.11		.	0.62	0.89	0.86	–	0.82	0.69	0.75
Carbon emissions (fossil fuel)	tC/cap/yr				0.48	0.75	0.63	0.82	–	0.61	0.74
Total DMC	t/cap/yr	0.15		0.24	0.58	0.75	0.80	0.69	0.61	–	0.68
GDP (purchasing power parity)	\$/cap/yr				0.75	0.79	0.69	0.75	0.74	0.68	–

production, the product mix and its efficiency, e.g. the input–output ratio of the livestock system. The volume and direction – import vs. export – of trade depends on both the national production level and each nation's socioeconomic status in terms of resource consumption and GDP. At the same time, trade can also affect the national land-use system, in addition to the multitude of socioeconomic, political, cultural and other factors that influence land use, for example if it is cheaper to import biomass-based resources than to produce them on national territory. The national land-use system is also affected by resource endowment, which we interpret in terms of a nation's biological production potential, not in terms of the availability of resources like minerals or fossil energy. Resource endowment is hence related to the availability of area, i.e. the inverse of population density, and suitability for agriculture (Krausmann et al., 2009b). Socioeconomic development status depends only partially on natural endowment and is heavily affected by factors outside the scope of the present analysis, i.e. historical contingencies.

3.2.1. *Population density*

Population density is well known to influence geographic patterns of material and energy use (Krausmann et al., 2008b; Steinberger et al., 2010) and HANPP (Krausmann et al., 2009b). These studies show that differences between countries in resource flows and HANPP per unit area (i.e. per m^2 and year) are strongly correlated with population density. The reason is that differences between countries in per-capita resource use are smaller than those in population density. The latter varies between countries by a factor of over 700. Therefore, the overall pattern of HANPP per unit area is largely determined by population density, despite the variation in per-capita flows.

But population density also influences the per-capita level of resource use. In general, material and energy flows as well as HANPP per capita and year are smaller in countries with higher population density and vice versa. There are several explanations that largely boil down to two mechanisms: (1) lower population density means higher resource endowment per capita, i.e. less incentive to use resources sparingly and (2) lower population density implies longer transport distances and hence more resource use required for transport and the related infrastructures (Krausmann et al., 2008b, 2009b; Steinberger et al., 2010). Our data confirm these hypotheses: eHANPP per unit area (kg/m^2/yr) and population density are strongly positively correlated ($R^2 = 0.85$, $p < 0.0001$, $N = 144$ countries with >98% of world population). As hypothesized, we find an inverse relation between per-capita eHANPP and population density, but the correlation is weaker ($R^2 = 0.27$, $p < 0.0001$, $N = 144$), and also weaker than that between HANPP on national territory per capita and population density ($R^2 = 0.35$, also inversely related). Because eHANPP per unit area largely follows the pattern of population density, and population density alone explains only

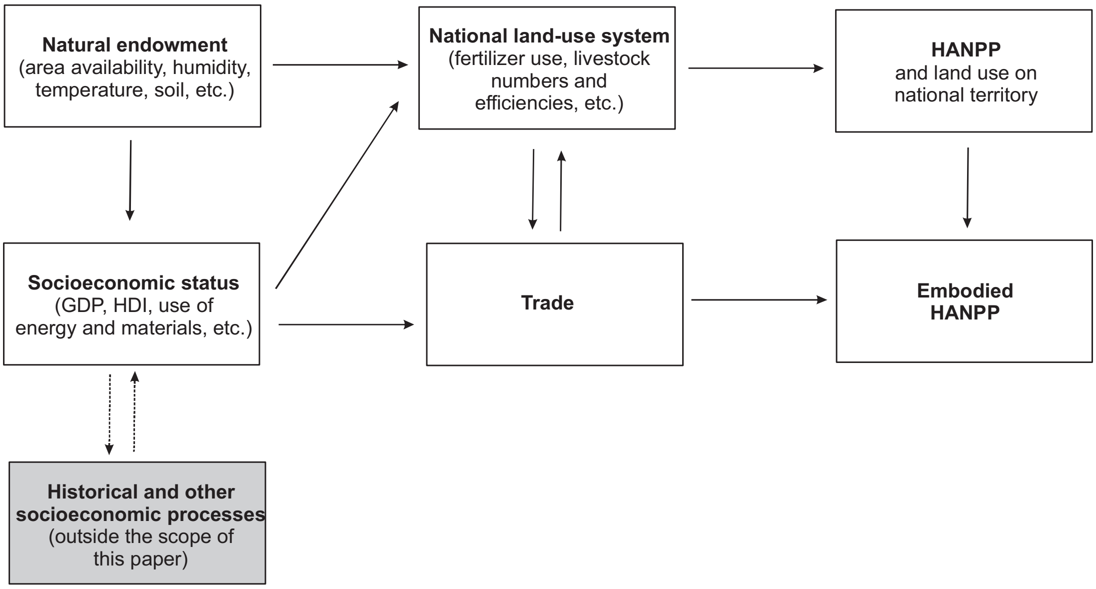

Fig. 2. Conceptual model of interdependencies underlying the statistical analyses presented in this paper. Solid lines indicate relations analysed in this paper and broken lines indicate relations beyond the scope of this paper.

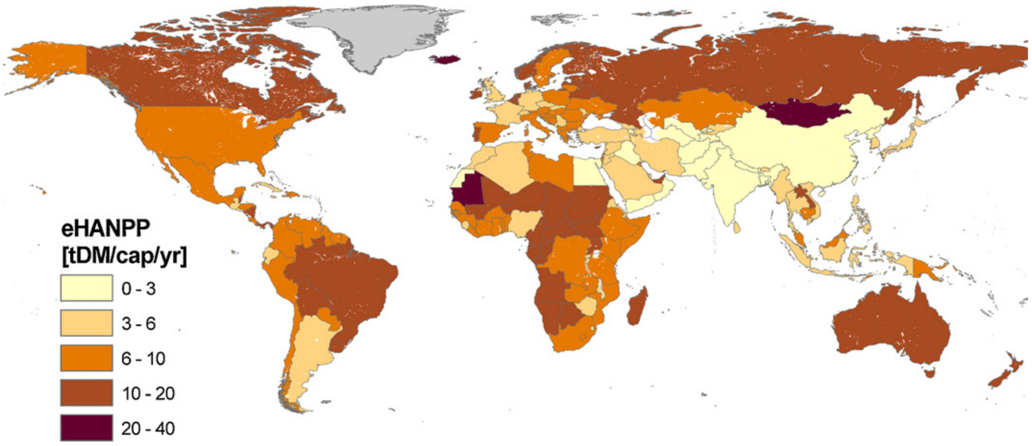

Fig. 3. Global map of eHANPP in tons dry matter per capita and year.
Map drawn based on data from Erb et al. (2009b).

a small proportion of the variation in per-capita eHANPP, we focus on the determinants of eHANPP per capita and year in the following section.

3.2.2. *Potential determinants of per-capita eHANPP*

Fig. 3 shows a world map of per-capita eHANPP in the year 2000. As discussed above, variations in HANPP on national territory explain about half of the global eHANPP pattern, while there is almost no correlation between eHANPP and GDP (Table 2). This suggests that the relationships analysed in the remainder of this subsection are complex.

In a first step, we analysed correlations between per-capita eHANPP, per-capita HANPP and some of their potential direct and indirect drivers according to Fig. 2. Coefficients of determination are displayed in Table 3. Looking at the first two columns we find that eHANPP and HANPP are largely correlated with the same factors, but the level of variation explained is mostly higher for HANPP than for eHANPP. Because eHANPP is defined as HANPP on national territory plus eHANPP related to net import, one might expect that net trade could help to explain the difference, but this is not the case. HANPP is inversely correlated with the eHANPP related to imports. This is plausible because countries with a large HANPP on national territory have ample means of supplying themselves and often others with biomass-based products. They tend to be 'net exporters' of HANPP (Erb et al., 2009b), hence the inverse correlation (negative 'net imports' are net exports). eHANPP per capita and year is not significantly correlated with the net import of eHANPP – countries with large per-capita eHANPP may have a high eHANPP due to their large domestic HANPP or they may be net eHANPP importers; similar considerations apply to countries with small per-capita eHANPP.

The factors explaining HANPP (and to a lesser extent eHANPP) are cropland area, livestock, domestic consumption of biomass and NPP_h, which is defined as biomass harvest plus biomass destroyed during harvest. As about half of the variation in per-capita eHANPP across countries results from variations in per-capita HANPP, and all of these factors are directly related with the national land use system, it seems plausible that these factors influence eHANPP through their effect on HANPP on national territory. There is only one indicator that is significantly correlated with eHANPP but not with HANPP, namely the final consumption of biomass, but this correlation is also weak ($R^2 = 0.11$).

eHANPP associated with net imports is inversely related not only with HANPP, but also with cropland area, the domestic consumption of biomass and NPP_h. All three indicators are correlated with per-capita HANPP, corroborating the hypothesis that countries

Table 3
Coefficient of determination (R^2) of the correlations between eHANPP, HANPP and their potential drivers. All variables per capita and year. $N > 142$. All correlations with $R^2 > 0.1$ are significant at $p > 0.001$; correlations with $R^2 < 0.1$ not displayed. Inverse relations are marked with an (I). All variables logged, except eHANPP of net imports (many negative values).

	eHANPP	HANPP	eHANPP net import	Cropland area	Livestock	Livestock efficiency	Biomass DMC	Biomass final cons	NPP_h	GDP
eHANPP [t/cap/yr]	–	0.48			0.17		0.34	0.11	0.29	
HANPP [t/cap/yr]	0.48	–	(I) 0.31	0.34	0.20		0.46		0.62	
eHANPP net import [t/cap/yr][a]		(I) 0.31	–	(I) 0.32	(I) 0.10		(I) 0.20		(I) 0.28	
Cropland [m^2/cap]		0.34	(I) 0.32	–			0.19		0.30	
Livestock [#/cap]	0.17	0.20	(I) 0.10		–	(I) 0.16	0.68		0.45	
Livestock efficiency [kg/#/yr][b]					(I) 0.16	–		0.45		0.59
Biomass DMC[c] [t/cap/yr]	0.34	0.46	(I) 0.20	0.19	0.68		–	0.18	0.69	
Biomass final cons.[d] [t/cap/yr]	0.11					0.45	0.18	–		0.75
NPP_h [t/cap/yr]	0.29	0.62	(I) 0.28	0.30	0.45	0.18	0.69		–	
GDP (PPP[e])						0.59		0.75		–

[a] Calculated as eHANPP – HANPP (both per capita and year); i.e. this is the eHANPP related to net imports. If HANPP on national territory exceeds eHANPP, a country is a net exporting country and this figure becomes negative.
[b] kg livestock products (dry matter) per head of livestock (measured in livestock units).
[c] Domestic material consumption of biomass-based products (=apparent consumption).
[d] Final consumption of biomass-based products (food, fibre, bioenergy, etc.).
[e] Purchasing power parities.

with a large resource endowment, and therefore high HANPP, large cropland and per-capita biomass flows, tend to be net 'exporters' of eHANPP.

Agrarian–industrial transitions are associated with strong GDP growth as well as with agricultural intensification, hence one can hypothesize that per-capita GDP should be correlated with HANPP, eHANPP and many other indicators related to agriculture. However, we found (Table 3) that GDP is not significantly correlated with any of the indicators except livestock efficiency, i.e. the tons of product generated in a country per livestock number and year, and the final consumption of biomass. These correlations are quite strong with $R^2 = 0.59$ and 0.75, respectively. Livestock efficiency mainly depends on the efficiency with which feed (roughage and market feed) is converted to meat, milk and eggs. Livestock efficiency rises with the transition from agrarian to industrial society, and is therefore correlated with per-capita GDP, for many reasons. Livestock has many functions in agrarian subsistence economies, e.g. status symbol, draft power, nutrient cycling, insurance against climate fluctuations, food production, etc., whereas in industrial economies the by far most important function is food production. Accordingly, livestock systems are optimized towards efficient biomass input–output relations in industrialized agriculture, but not necessarily in agrarian societies (Krausmann et al., 2009b).

The lacking correlations between GDP and the other indicators can be interpreted as follows. The strong correlation of final biomass consumption with GDP indicates that GDP may be causally linked with the consumption of biomass-based products. The lacking correlation between GDP and HANPP as well as eHANPP suggests that there are possibilities for 'decoupling' final biomass consumption from HANPP, and even from the domestic consumption of biomass – remember that this is the 'apparent consumption' of primary biomass which is dominated by bulk flows of primary biomass such as hay, wood and primary crops, while product flows like food, furniture or paper are much smaller. This hypothesis is supported by the strong correlation ($R^2 = 0.45$) between livestock efficiency and final biomass consumption: an efficient livestock system is key for decoupling the domestic biomass consumption from the final consumption of biomass, and countries with high GDP and high final biomass consumption also have efficient livestock systems.

3.2.3. *Natural determinants of national land-use systems*

As discussed in the last subsection, the national land-use system strongly affects eHANPP patterns, despite the relevance of trade. Factors that could potentially determine the characteristics of the national land-use system are analysed in Table 4. NPP_0 is the yearly NPP of potential natural vegetation, i.e. the vegetation that would prevail in the absence of land use. While NPP_0 per unit area mainly depends on climate and soil, NPP_0 per capita – i.e. the natural productivity potential available in a country per person – is strongly affected by a country's productive area available for each inhabitant and can therefore be interpreted as an indicator of resource endowment. Hence the strong correlation between per-capita NPP_0, productive land area, cropland area, NPP_h and domestic biomass consumption ('biomass DMC'): countries with a large resource endowment can achieve higher production levels per capita, sustain larger per-capita biomass flows (DMC) and have more livestock – however, that latter effect is weak ($R^2 = 0.11$).

NPP_0 and productive land per capita does not translate into final biomass consumption, indicating that countries with small resource endowment have other means at their disposal to achieve higher consumption, i.e. more efficient production and trade. The inverse correlations between NPP_0 and productive land and livestock efficiency suggest that countries with large resource endowment tend to have a less efficient livestock system – a finding consistent with qualitative knowledge about livestock systems

Table 4
Coefficient of determination (R^2) of the correlations between variables characterizing the national land-use system and its potential natural determinants. All variables per capita and year, except for cropland suitability, mean temperature and precipitation. $N > 147$. All correlations with $R^2 > 0.1$ are significant at $p < 0.001$; correlations with $R^2 < 0.1$ not displayed. Inverse relations are marked with an (I). All variables logged (zeros and negatives removed).

	NPP_0	Product. land	Mean temp.	Mean precip.	Latitude	Cropland area	Fertilizer	Livestock	Livestock output	Livestock efficiency	NPP_h	Biomass DMC	Final cons.	eHANPP import
NPP_0 [a]	–	0.80		0.19	(I) 0.11	0.55		0.11		(I) 0.12	0.46	0.28		(I) 0.30
Productive land area[b]	0.80	–				0.88		0.19		(I) 0.11	0.43	0.30		(I) 0.24
Mean temperature[c]			–		(I) 0.46		(I) 0.17		(I) 0.41	(I) 0.36			(I) 0.26	
Mean precipation[d]	0.19			–	(I) 0.14									
Abs. mean latitude[e]	(I) 0.11		(I) 0.46	(I) 0.14	–		0.23		0.38	0.21			0.24	
Cropland area[b]	0.55	0.88				–		0.17			0.29	0.24		(I) 0.32
Fertilizer use[a]			(I) 0.17		0.23		–		0.46			0.13	0.41	
Livestock[f]	0.11	0.19				0.17		–	0.22	(I) 0.16	0.45	0.68		(I) 0.10
Livestock output[a]			(I) 0.41		0.38		0.46	0.22	–	0.39		0.34	0.55	
Livestock efficiency[g]	(I) 0.12	(I) 0.11	(I) 0.36		0.21		0.30	(I) 0.16	0.39	–			0.45	
NPP_h [a]	0.46	0.43				0.29		0.45			–	0.69		(I) 0.28
Biomass DMC[a]	0.28	0.30				0.24	0.13	0.68	0.34		0.69	–	0.18	(I) 0.20
Final biomass cons.[a]			(I) 0.26		0.24		0.41		0.55	0.45		0.18	–	
eHANPP imports[h]	(I) 0.30	(I) 0.24				(I) 0.32		(I) 0.10			(I) 0.28	(I) 0.20		–

[a] t/cap/yr.
[b] m²/cap.
[c] °C.
[d] mm/yr.
[e] Degrees.
[f] Livestock units per capita.
[g] Tons of livestock products per livestock unit per year.
[h] Calculated as eHANPP – HANPP (both per capita and year); i.e. this is the eHANPP related to net imports. If HANPP on national territory exceeds eHANPP, a country is a net exporting country and this figure becomes negative.

Table 5

Coefficient of determination (R^2) of the correlations between variables characterizing the national land-use system and its potential socioeconomic determinants. All variables per capita and year, except where inappropriate (e.g., % values). $N > 139$. All correlations with $R^2 > 0.1$ are significant at $p < 0.001$; correlations with $R^2 < 0.1$ not displayed. Inverse relations are marked with an (I). All variables logged (zeros and negatives removed).

	GDP	Agric. GDP%	Agric. GDP per cap	Urbanization	Agric. population	Fertilizer use	Livestock units	Livestock output	Livestock efficiency	Final biomass cons.
GDP (PPP)[a]	–	(I) 0.74	0.14	0.50	(I) 0.73	0.42		0.59	0.59	0.75
Agricultural GDP [%]	(I) 0.74	–		(I) 0.44	0.67	(I) 0.20		(I) 0.37	(I) 0.46	(I) 0.51
Agricultural GDP per cap[a]	0.14		–			0.25		0.16		0.17
Urbanization[b]	0.50	(I) 0.44		–	(I) 0.51	0.20		0.40	0.36	0.34
Agricult. population[c]	(I) 0.73	0.67		(I) 0.51	–	(I) 0.23		(I) 0.47	(I) 0.67	(I) 0.57
Fertilizer use[d]	0.42	(I) 0.20	0.25	0.20	(I) 0.23	–		0.46	0.30	0.41
Livestock units[e]							–	0.22	(I) 0.16	
Livestock output[d]	0.59	(I) 0.37	0.16	0.40	(I) 0.47	0.46	0.22	–	0.39	0.55
Livestock efficiency[f]	0.59	(I) 0.46		0.36	(I) 0.67	0.30	(I) 0.16	0.39	–	0.45
Final biomass cons.[d]	0.75	(I) 0.51	0.17	0.34	(I) 0.57	0.41		0.55	0.45	–

[a] \$/cap/yr.

[b] Percentage of population at mid-year residing in urban areas.

[c] Agricultural population as percentage of total population based on the FAO definition (people active in agriculture, forestry, fishing and hunting plus their non-working dependents).

[d] kg/cap/yr.

[e] Number of livestock units per capita.

[f] kg/livestock unit per year.

across the globe (FAO, 2006b). NPP_0, productive land, cropland availability, livestock numbers, NPP_h and biomass DMC are all inversely correlated with the eHANPP related to net imports. This is plausible: large resource endowment results in little dependency on imports and rather enables countries to have an export surplus – in this latter case there is a negative eHANPP related to imports, hence the inverse correlation.

Because productivity is positively related with temperature and precipitation, one might expect that NPP_0, NPP_h and other biomass flow variables are positively correlated with both climate variables in our sample, even though there are of course other factors (e.g., soil and topography) that influence productivity. We find only a small positive effect of precipitation on NPP_0, no correlation with any other variable, and even a negative effect of temperature on some other variables in our sample. Because there is no correlation of the climate variables or latitude with per-capita availability of productive land, this outcome does not seem to be related to differences in population density. A look at the geographic variable 'absolute mean latitude' helps to better understand that pattern: towards the poles, temperatures get lower and precipitation declines; suitability for farming is usually best at intermediate latitudes (about 30–55° north and south) with humid climate. On the other hand, affluence-related variables do not show such an unimodal pattern, but positively correlate with latitude: fertilizer use (strongly correlated with GDP, see below), livestock output and livestock efficiency as well as final biomass consumption. In other words, the pattern expected to result from the effect of natural factors seems to be counteracted by socioeconomic variables.

When looking at the correlations between the various land-use system indicators, we find strong, positive correlations between livestock numbers and NPP_h as well as livestock numbers and biomass DMC. This is to be expected, as livestock consumes a large fraction (globally more than half) of the used biomass harvest (Krausmann et al., 2008a). Final biomass consumption is strongly correlated with livestock output and livestock efficiency, as well as with fertilizer use. This corroborates the hypotheses formulated in the last subsection on the interrelation between GDP and changes in the land-use system.

3.2.4. Socioeconomic determinants of national land-use systems

The analysis of socioeconomic variables (Table 5) largely provides additional evidence for the hypothesis that changes in land use during agrarian–industrial transitions, and hence along GDP gradients (Fischer-Kowalski and Haberl, 2007; Sieferle et al., 2006), are by and large mirrored in cross-country data. According to this hypothesis, GDP should be inversely correlated with the share of agricultural GDP in total GDP as well as with the share of agricultural population in total population, which is exactly what we found in our dataset. As one would expect based on the above-formulated hypothesis, we found positive, often strong, correlations between GDP, urbanization, fertilizer use, per-capita livestock output, livestock efficiency as well as final biomass consumption.

The other correlations are also consistent with the above-cited long-term case studies. We did not find a significant correlation between GDP (and the other variables shown in Table 5 that are correlated with GDP) and indicators for land demand. For example, cropland area was not at all correlated with GDP. R^2 of the correlations of embodied HANPP related to imports with the variables displayed in Table 5 was at or below 0.1 and therefore omitted. Whether a country is net importer or exporter is most likely not related to its affluence but rather to other characteristics such as its resource endowment (see above).

4. Outlook and conclusions

The first part of our analysis suggests that there is a fundamental difference between (1) indicators that account for socioeconomic metabolism and (2) indicators related to effects of land use on ecosystems, e.g. HANPP. Indicators of socioeconomic metabolism such as TPES, DEC, DMC, EF and CO_2 emissions measure resource use in uniform units at the input or output of economies and are strongly correlated with one another.

By contrast, land-use related indicators such as HANPP and eHANPP are useful to monitor a fundamentally different aspect of resource use, i.e. the human use of the bioproductive capacity of ecosystems. They do not account for resources entering or exiting an economy, but rather indicate the implications of the extraction of resources for the ecosystems where the resources are extracted, in terms of its share of local primary productivity. Rapid loss of biodiversity (Pimm and Raven, 2000) and the ongoing global degradation of ecosystems as well as their capacity to deliver vital services to humanity (Millennium Ecosystem Assessment, 2005), both strongly related to land-use change, suggest that this is an important dimension of resource use. The poor correlation between resource throughput indicators and HANPP as well as eHANPP demonstrates that impacts of land-use on ecosystems (which have been shown to be related to HANPP, see Section 2.1) are not well captured by resource flow indicators.

Our results therefore suggest that it is essential to include land-use related indicators such as HANPP or eHANPP in any indicator system that aims to consider land-use related impacts in monitoring progress towards sustainability. Which of the highly correlated indicators related to socioeconomic metabolism (DMC, DEC, TPES, EF, CO_2 etc.) need to be included depends on the purpose and context of the respective indicator system or the study objectives. Efforts to improve existing HANPP databases and indicators should therefore be undertaken. For example, at present relatively robust global spatially explicit HANPP data exist only for the year 2000, and these data could benefit from further improvements (Haberl et al., 2007). Global totals of the eHANPP data used for this study (Erb et al., 2009b) are consistent with that database and hence seemed robust enough for the exploratory analysis presented here, but the disaggregation of products used in that study as well as the net-trade concept used therein limits the scope of that dataset. More informative eHANPP data could be derived from bilateral trade matrices which would require massive efforts beyond the scope of this paper.

Our analysis of the determinants of eHANPP per capita showed that approximately half of the variation of per-capita eHANPP can be explained by the variation of per-capita HANPP. Thus the national land-use system is an important determinant of its per-capita eHANPP, but trade is also relevant. Resource endownment of a nation plays a critical role because resource-rich, sparsely populated areas tend to be net exporters of eHANPP, i.e. their eHANPP is smaller than their HANPP on national territory. We found that resource endowment tends to result in a larger per-capita HANPP as well as larger per-capita eHANPP. However, resource endowment is not correlated with final biomass consumption, suggesting that countries compensate lacking domestic production potential through trade.

In contrast to resource use indicators related to socioeconomic metabolism, affluence does not play a strong role in determining per-capita eHANPP. eHANPP can be small or large in both rich and poor countries. This suggests that it is possible to 'decouple' GDP from eHANPP. In contrast to HANPP and eHANPP, the final consumption of biomass is strongly correlated with GDP ($R^2 = 0.75$), suggesting that this decoupling does not imply that affluent countries consume less biomass-based products but rather that they have means to reduce eHANPP per unit of final biomass consumption so that increases in the final consumption of biomass resulting from GDP growth do not translate into increases of eHANPP.

The 'decoupling' between eHANPP and GDP as well as final biomass consumption can largely be explained by technological changes that occur during transitions from agrarian to industrial society, and hence along GDP gradients, in all countries, although perhaps to a different degree and with different rates (Fischer-Kowalski and Haberl, 2007): agricultural intensification is strongly related with GDP growth and results in the following changes in the land system (Erb et al., 2009a):

- NPP of agroecosystems increases which reduces the difference between potential and actual NPP (ΔNPP_{LC}).
- The harvestable proportion of crop plants, i.e. their harvest index, is increased which helps to raise final biomass consumption per unit of NPP_h.
- The feeding efficiency of the livestock improves strongly which also helps to reduce NPP_h per unit of final biomass consumption (Haberl et al., 2011).

Such positive effects of agricultural intensification notwithstanding there are also many substantial environmental costs of intensification, such as nitrogen leaching, soil loss, pressures on biodiversity, deterioration of the agricultural energy return on investment and many more (e.g., IAASTD, 2009; Pimentel et al., 1990), suggesting a need to consider a multitude of sometimes conflicting criteria in optimizing land-use systems (Tilman et al., 2002; Lambin and Meyfroidt, 2011). Although HANPP and eHANPP cover important aspects of land use, complementing them with indicators that address aspects of agricultural intensification that are at present not sufficiently covered (e.g., mechanization, chemical inputs or yields) would help to generate more comprehensive, robust indicator systems.

Acknowledgements

This research was funded by the Austrian Science Fund (FWF) within the project P20812-G11 and by the EU-FP7 project VOLANTE (Visions of Land-Use Transitions in Europe). It contributes to the Global Land Project (http://www.globallandproject.org). We gratefully acknowledge comments by two anonymous reviewers which have helped a lot to improve the paper.

References

Ahn, C.-H., Tateishi, R., 1994. Development of global evapotranspiration and water balance data sets. Journal of Japan Society of Photogrammetry and Remote Sensing 33, 48–61.

Ayres, R.U., Simonis, U.E. (Eds.), 1994. Industrial Metabolism: Restructuring for Sustainable Development. United Nations University Press, Tokyo, New York, Paris.

Bastianoni, S. (Ed.), 2012. The State of the Art in Ecological Footprint: Theory and Applications. Ecological Indicators, vol. 16, pp. 1–166, Special issue.

Boyden, S.V., 1992. Biohistory: The Interplay Between Human Society and the Biosphere—Past and Present. UNESCO and Parthenon Publishing Group, Paris.

CDIAC, 2007. Trends: A Compendium of Data on Global Change, compiled by G. Marland, T.A. Boden, and R.J. Andres. Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN.

Costanza, R., 1991. Ecological Economics: The Science and Management of Sustainability. Columbia University Press, New York.

Crutzen, P.J., Steffen, W., 2003. How long have we been in the anthropocene era? Climatic Change 61, 251–257.

Deichmann, U., Eklundh, L., 1991. Global Digital Data Sets for Land Degradation Studies: A GIS Approach. UNEP/GEMS and GRID, Nairobi, Kenya.

Dunlap, R.E., Catton, W.R., 2002. Which function(s) of the environment do we study? A comparison of environmental and natural resource sociology. Society and Natural Resources 15, 239–249.

EEA, 2010. The European Environment—State and Outlook 2010: Synthesis. European Environment Agency, Copenhagen.

Erb, K.-H., Gaube, V., Krausmann, F., Plutzar, C., Bondeau, A., Haberl, H., 2007. A comprehensive global 5 min resolution land-use dataset for the year 2000 consistent with national census data. Journal of Land Use Science 2, 191–224.

Erb, K.-H., Gingrich, S., Krausmann, F., Haberl, H., 2008. Industrialization, fossil fuels and the transformation of land use: an integrated analysis of carbon flows in Austria 1830–2000. Journal of Industrial Ecology 12, 686–703.

Erb, K.-H., Krausmann, F., Gaube, V., Gingrich, S., Bondeau, A., Fischer-Kowalski, M., Haberl, H., 2009a. Analyzing the global human appropriation of net primary production—processes, trajectories, implications. An introduction. Ecological Economics 69, 250–259.

Erb, K.-H., Krausmann, F., Lucht, W., Haberl, H., 2009b. Embodied HANPP: mapping the spatial disconnect between global biomass production and consumption. Ecological Economics 69, 328–334.

ESRI, 2004. Data and Maps. Environmental Systems Research Institute (ESRI), Redlands, CA [CD-ROM].

FAO, 2006a. FAOSTAT 2006, FAO Statistical Databases: Agriculture, Fisheries, Forestry, Nutrition. Food and Agriculture Organization of the United Nations (FAO), Rome.

FAO, 2006b. Livestock's Long Shadow—Environmental Issues and Options. Food and Agriculture Organisation of the United Nations, Rome, pp. 1–408.

Fischer-Kowalski, M., 1998. Society's metabolism. The intellectual history of material flow analysis. Part I: 1860–1970. Journal of Industrial Ecology 2, 61–78.

Fischer-Kowalski, M., Haberl, H. (Eds.), 2007. Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar, Cheltenham, UK/Northhampton, USA.

Fischer-Kowalski, M., Hüttler, W., 1998. Society's metabolism. The intellectual history of material flow analysis. Part II: 1970–1998. Journal of Industrial Ecology 2, 107–137.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Gerbens-Leenes, P.W., Hoekstra, A.Y., Meer, Th.V.D., 2009. The water footprint of energy from biomass: a quantitative assessment and consequences of an increasing share of bio-energy in energy supply. Ecological Economics 68, 1052–1060.

Graedel, T.E., Cao, J., 2010. Metal spectra as indicators of development. Proceedings of the National Academy of Sciences of the United States of America 107, 20905–20910.

Haberl, H., 1997. Human appropriation of net primary production as an environmental indicator: implications for sustainable development. Ambio 26, 143–146.

Haberl, H., 2001. The energetic metabolism of societies. Part I: Accounting concepts. Journal of Industrial Ecology 5, 11–33.

Haberl, H., Schulz, N.B., Plutzar, C., Erb, K.-H., Krausmann, F., Loibl, W., Moser, D., Sauberer, N., Weisz, H., Zechmeister, H.G., Zulka, P., 2004a. Human appropriation of net primary production and species diversity in agricultural landscapes. Agriculture, Ecosystems & Environment 102, 213–218.

Haberl, H., Wackernagel, M., Krausmann, F., Erb, K.-H., Monfreda, C., 2004b. Ecological footprints and human appropriation of net primary production: a comparison. Land Use Policy 21, 279–288.

Haberl, H., Plutzar, C., Erb, K.-H., Gaube, V., Pollheimer, M., Schulz, N.B., 2005. Human appropriation of net primary production as determinant of avifauna diversity in Austria. Agriculture, Ecosystems & Environment 110, 119–131.

Haberl, H., Weisz, H., Amann, C., Bondeau, A., Eisenmenger, N., Erb, K.-H., Fischer-Kowalski, M., Krausmann, F., 2006. The energetic metabolism of the European Union and the United States: decadal energy input time-series with an emphasis on biomass. Journal of Industrial Ecology 10, 151–171.

Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences 104, 12942–12947.

Haberl, H., Erb, K.-H., Krausmann, F., Berecz, S., Ludwiczek, N., Musel, A., Schaffartzik, A., Martinez-Alier, J., 2009. Using embodied HANPP to analyze teleconnections in the global land system: conceptual considerations. Geografisk Tidsskrift—Danish Journal of Geography 109, 119–130.

Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzar, C., Steinberger, J.K., 2011. Global bioenergy potentials from agricultural land in 2050: sensitivity to climate change, diets and yields. Biomass and Bioenergy 35, 4753–4769.

Hak, T., Moldan, B., Dahl, A.L. (Eds.), 2012. Indicators of Environmental Sustainability: From Concept to Applications, vol. 17, pp. 1–126, Special issue.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.J., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25, 1965–1978.

Hoekstra, A.Y., Hung, P.Q., 2005. Globalisation of water resources: international virtual water flows in relation to crop trade. Global Environmental Change 15, 45–56.

IAASTD, 2009. Agriculture at a Crossroads. International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), Global Report. Island Press, Washington, DC.

IEA, 2007a. Energy Balances of Non-OECD Countries, 2004–2005—2007 Edition. International Energy Agency (IEA), Organisation of Economic Co-Operation and Development (OECD).

IEA, 2007b. Energy Balances of OECD Countries, 2004–2005 – 2007 Edition. International Energy Agency (IEA), Organisation of Economic Co-Operation and Development (OECD).

Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., Lawrence, W.T., 2004. Global patterns in human consumption of net primary production. Nature 429, 870–873.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom/New York, USA.

Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., Haberl, H., 2008a. Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints. Ecological Economics 65, 471–487.

Krausmann, F., Fischer-Kowalski, M., Schandl, H., Eisenmenger, N., 2008b. The global socio-metabolic transition: past and present metabolic profiles and their future trajectories. Journal of Industrial Ecology 12, 637–656.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., Fischer-Kowalski, M., 2009a. Growth in global materials use, GDP and population during the 20th century. Ecological Economics 68, 2696–2705.

Krausmann, F., Haberl, H., Erb, K.-H., Wiesinger, M., Gaube, V., Gingrich, S., 2009b. What determines geographical patterns of the global human appropriation of net primary production? Journal of Land Use Science 4, 15–34.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences 108, 3465–3472.

Larsen, H.N., Hertwich, E.G., 2010. Identifying important characteristics of municipal carbon footprints. Ecological Economics 70, 60–66.

Lauk, C., Erb, K.-H., 2009. Biomass consumed in anthropogenic vegetation fires: global patterns and processes. Ecological Economics 69, 301–318.

Martinez-Alier, J., 1987. Ecological Economics. Energy, Environment and Society. Blackwell, Oxford.

Matthews, E., Amann, C., Fischer-Kowalski, M., Bringezu, S., Hüttler, W., Kleijn, R., Moriguchi, Y., Ottke, C., Rodenburg, E., Rogich, D., Schandl, H., Schütz, H., van der Voet, E., Weisz, H., 2000. The Weight of Nations: Material Outflows from Industrial Economies. World Resources Institute, Washington, DC.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being—Our Human Planet. Summary for Decision Makers. Island Press, Washington, DC.

OECD, 2008. Measuring Material Flows and Resource Productivity. Synthesis Report. Organisation for Economic Co-operation and Development (OECD), Paris.

Peters, G.P., Hertwich, E.G., 2008. CO_2 embodied in international trade with implications for global climate policy. Environmental Science and Technology 42, 1401–1407.

Pimentel, D., Dazhong, W., Giampietro, M., 1990. Technological changes in energy use in U.S. agricultural production. In: Gliessman, S.R. (Ed.), Agroecology, Researching the Ecological Basis for Sustainable Agriculture. Springer, New York, pp. 305–321.

Pimm, S.L., Raven, P.H., 2000. Biodiversity: extinctions by numbers. Nature 403, 843–845.

Ramankutty, N., Foley, J.A., Norman, J., McSweeney, K., 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Global Ecology and Biogeography 11, 377–392.

Sieferle, R.P., Krausmann, F., Schandl, H., Winiwarter, V., 2006. Das Ende der Fläche. Zum gesellschaftlichen Stoffwechsel der Industrialisierung. Böhlau, Köln.

Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The anthropocene: are humans now overwhelming the great forces of nature. Ambio 36, 614–621.

Steinberger, J.K., Krausmann, F., 2011. Material and energy productivity. Environmental Science and Technology 45, 1169–1176.

Steinberger, J.K., Roberts, J.T., 2010. From constraint to sufficiency: the decoupling of energy and carbon from human needs, 1975–2005. Ecological Economics 70, 425–433.

Steinberger, J.K., Krausmann, F., Eisenmenger, N., 2010. Global patterns of material use: a socioeconomic and geophysical analysis. Ecological Economics 69, 1148–1158.

The World Bank Group, 2007. World Development Indicators 2007. The World Bank, Washington, DC.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Turner, B.L.I., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Sciences of the United States of America 104, 20666–20671.

UN, 2008. World Urbanization Prospects: The 2007 Revision. United Nations, Department of Economic and Social Affairs, Population Division, New York.

UNEP, 2007. Global Environment Outlook 4: Environment for Development. United Nations Environment Programme. Progress Press Ltd., Valetta, Malta.

Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., Matson, P.A., 1986. Human appropriation of the products of photosynthesis. BioScience 36, 363–373.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of earth's ecosystems. Science 277, 494–499.

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R.B., Randers, J., 2002. Tracking the ecological overshoot of the human economy. Proceedings of the National Academy of Sciences of the United States of America 99, 9266–9271.

WBGU, 2011. World in Transition—A Social Contract for Sustainability. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU), Berlin.

Weisz, H., Krausmann, F., Amann, C., Eisenmenger, N., Erb, K.-H., Hubacek, K., Fischer-Kowalski, M., 2006. The physical economy of the European Union: cross-country comparison and determinants of material consumption. Ecological Economics 58, 676–698.

Whittaker, R.H., Likens, G.E., 1973. Primary production: the biosphere and man. Human Ecology 1, 357–369.

Wiedmann, T., 2009. A first empirical comparison of energy footprints embodied in trade—MRIO versus PLUM. Ecological Economics 68, 1975–1990.

Wright, D.H., 1990. Human impacts on the energy flow through natural ecosystems, and implications for species endangerment. Ambio 19, 189–194.