Embodied HANPP: Mapping the spatial disconnect between global biomass production and consumption

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Keywords: Land use, Net primary production, Global environmental change, Socioeconomic biomass flows, Production and consumption patterns

Ecological Economics

Special Section "Analyzing the global human appropriation of net primary production: Trajectories, processes and implications"

Guest editors: Karl-Heinz Erb, Helmut Haberl, Fridolin Krausmann

Published as:
Karl- Heinz Erb, Fridolin Krausmann, Wolfgang Lucht , Helmut Haberl (2009). Embodied HANPP: Mapping the spatial disconnect between biomass production and consumption. *Ecological Economics* **69**(2), 328-334. doi: 10.1016/j.ecolecon.2009.06.025

Abstract

Biomass trade results in a growing spatial disconnect between environmental impacts due to biomass production and the places where biomass is being consumed. The pressure on ecosystems resulting from the production of traded biomass, however, is highly variable between regions and products.We use the concept of embodied human appropriation of net primary production (HANPP) to map the spatial disconnect between net-producing and net-consuming regions. Embodied HANPP comprises total biomass withdrawals and land use induced changes in productivity resulting from the provision of biomass products. International net transfers of embodied HANPP are of global significance, amounting to 1.7 PgC/year. Sparsely populated regions are mainly net producers, densely populated regions net consumers, independent of development status. Biomass consumption and trade are expected to surge over the next decades, suggesting a need to sustainably manage supply and demand of products of ecosystems on a global level.

1. Introduction

Understanding the interplay of society and ecosystems in shaping patterns and processes within the global land system (Turner et al., 2007) is a prerequisite for society's ability to succeed in mastering the sustainability challenge (Kates et al., 2001; Carpenter et al., 2006). Current and expected trends of global population growth, changes in human diet and the growth of global bioenergy demand will lead to drastic increases in the demand for provisioning services of ecosystems (Tilman,1999), jeopardizing the supply of other ecosystemservices and posing a threat to the resilience of coupled socio-ecological systems (Lenton et al., 2008), and ultimately to the future of human society (Millenium Ecosystem Assessment, 2005; Foley et al., 2005). Attempts to analyze the interaction of society and the biosphere (Steffen et al., 2007), however, are complicated by the wide range of spatial and temporal scales on which the interaction takes place (Costanza et al., 2007). Globalization, along with current trends in urbanization, has fundamentally altered the spatial scales on which these interactions occur, affecting both the demand for and the supply of ecosystem services (Bennett and Balvanera, 2007). Trade has long been contributing to breaking the local links between production and consumption of natural resources once held in place by limited transport capacities (Chisholm, 1990). In recent times, however, the rapid growth of the volume of biomass trade (food, feed, fibre, biofuels, animals, etc.) results in a surging spatial disconnect between the places where environmental impacts related to biomass production occur, and the places where biomass is being consumed.

Analyses of the causal relationships between socioeconomic drivers of land use, such as biomass consumption, and its impacts on ecosystems, must take this spatial disconnect into account. Such analyses, however, are hampered by the fact that the amount of biomass contained in traded products is small compared to the upstream flows involved in their production (Vitousek et al., 1997; Imhoff et al., 2004; Haberl et al., 2007; Krausmann et al., 2008). On the global average, for each ton of final biomass product (measured as dry matter), 3.1 tons of dry matter biomass is harvested, 1.7 tons is lost or destroyed during harvest (Krausmann et al., 2008) and 3.2 tons of net primary production is foregone (Haberl et al., 2007). Net primary production (NPP) is the amount of biomass produced by green plants through photosynthesis each year. The term "NPP foregone" here denotes the change in NPP

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due to land conversion associated with the production of the respective product(s). This parameter is abbreviated asΔNPPLC (Haberl et al., 2007; Erb et al., 2009-this issue). The magnitude of these upstream flows is highly product-specific and region-specific, because it depends on the life cycle of each product and on the characteristics of local production systems. Trade flow data as reported in international trade statistics are therefore insufficient to link drivers and impacts. For example, a country that imports 1000 tons ofmeat and exports 1000 tons of cereals annually would exert a much larger pressure on ecosystems globally than this physical trade balance would suggest, because the production of meat is associated with much larger upstream requirements of biomass than that of cereals.

We here present an account of the global spatial disconnect between the location of biomass production and consumption which systematically refers to the pressure on ecosystems related to the consumption of biomass products. For each ton of biomass consumed we calculate the amount of the net primary production (NPP) appropriated in the course of its production. The human appropriation of NPP (HANPP) has been defined as the aggregate effect of land conversion and biomass harvest on the amount of NPP available per year for ecosystem processes (Haberl et al., 2007; Erb et al., 2009-this issue). HANPP calculations account for three NPP components: (a) primary biomass withdrawn from ecosystems through socioeconomic harvest of biomass for food, feed, fibre and fuel, (b) NPP losses, i.e. biomass destroyed during harvest and left on site (e.g. felling losses, agricultural residues), and (c) NPP foregone due to the fact that the productivity of human-dominated ecosystems deviates from the productivity of the natural ecosystems they replace (ΔNPP_{LC}).
HANPP maps are calculated based on land use data, vegetation modelling and agricultural/forestry statistics, all of which are independent from population density, and describe the geographic origin of biomass, not the place where it is used (Haberl et al., 2007). Thus, HANPP maps are suitable for analyzing impacts on ecosystem patterns and functioning, such as changes in biodiversity or alterations of biogeochemical cycles (Vitousek et al., 1997; Erb et al., 2009-this issue), but do not allow for straightforward analyses of socioeconomic drivers of land use, such as the consumption of biomass products (Krausmann et al., 2009). Embodied HANPP evaluates the amount of HANPP resulting from the whole production chain of biomass products, such as food, feed, bioenergy, wood products, clothing or others, including agricultural or forestry production aswell as changes in NPP resulting from land conversion (ΔNPP_{LC}). Embodied HANPP allows to attribute to each product the amount of HANPP resulting from its production.

2. Methods

The quantification of the spatial disconnect between biomass production and consumption is based on a comparison of the HANPP map published by Haberl et al. (2007) with a map of the consumption of embodied HANPP in the year 2000. Both maps have a resolution of 5 arc min; that is, approximately 10×10 km at the equator. Based on this comparison we identify net-producing and net-consuming areas which we consequently analyze on the country level. The map of embodied HANPP consumption (Fig. 1 below) is constructed as follows. In a first step, total HANPP embodied in the biomass consumption of each country is calculated. This calculation refers to the national apparent consumption of biomass; that is, domestic extraction of biomass plus imports minus exports of biomass-derived products. In a second step we calculate national per-capita consumption of embodied HANPP and use a population

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density map to construct a map of the consumption of embodied HANPP at the subnational level as explained below.
The national consumption of embodied HANPP is calculated as the sum of HANPP occurring on a country's territory, i.e. the upstream NPP flow associated with domestic biomass harvest as presented by Haberl et al. (2007), plus the HANPP related to biomass imports minus the HANPP related to biomass exports. HANPP equivalents of import and export of biomass products are calculated using multipliers derived from an existing database (Krausmann et al., 2008) applied to national-level data on trade flows taken from the FAO. These multipliers are calculated for each country as the ratio of socioeconomic biomass outputs in metric tons of dry matter biomass per year (food, fibre, timber, biofuels, exports) to the sum of the following biomass inputs: (a) primary crops, (b) used crop residues, (c) biomass harvested from grassland and grazed biomass, (d) wood harvest (removals), (e) unrecovered crop residues and residues from wood harvest, (f) belowground biomass of harvested primary crops and felled trees, (g) imports, (h) ΔNPP_{LC} on agricultural and forestry lands and (i) ΔNPPLC related to the infrastructure required for biomass production and trade (Haberl et al., 2007). As biomass accounts for 40% of global resource extraction (Schandl and Eisenmenger, 2006), we assume that flow (i) amounts to 40% of total national ΔNPP_{LC} caused by rural infrastructure (Haberl et al., 2007). The calculation of embodied HANPP flows associated with exports is based on national level multipliers for each country. Embodied HANPP flows associated with imports are calculated as the weighted average of the multipliers of all net-exporting countries.

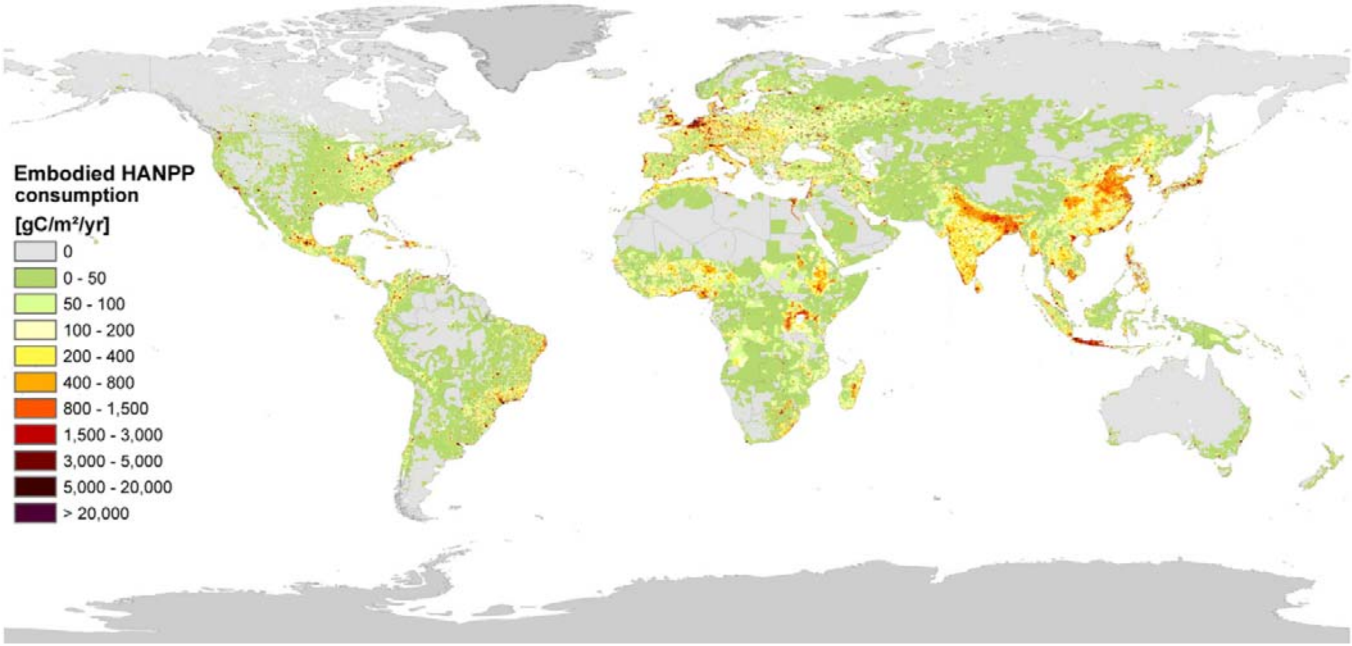

Fig. 1. Embodied HANPP associated with domestic biomass consumption in each grid cell. The map expresses HANPP equivalents of the apparent consumption of biomass products (domestic production plus imports minus exports) in gC/m^2/year.

Per-capita consumption of embodied HANPP is calculated by dividing the consumption of embodied HANPP in each country by the country's population. Using a population density map with a resolution of 5′ (CIESIN and CIAT, 2006), we allocate the national per capita embodied HANPP consumption to grid cells. Gridded population density data can serve as a proxy of spatial patterns of biomass consumption, because previous analyses (Krausmann et

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al., 2008, 2009) have shown that the relation between per capita biomass demand and population density is highly significant, whereas dietary patterns, technology and development status play a less important, income (GDP) a negligible role. Furthermore, population density is the only potential proxy where gridded data are available today. The approach followed here neglects potential subnational differences, but takes variations between countries in technology, diet and development status at the national level explicitly into account. It is important to note, however, that no population density data enter the construction of the maps of HANPP as well as the national-level maps of embodied HANPP. Only the gridded map of the consumption of embodied HANPP (Fig. 1) is based on population (density) data. A gridded map of the spatial disconnect between HANPP and the consumption of embodied HANPP (Fig. 2a) is constructed by subtracting the map of the consumption of embodied HANPP (Fig. 1) from the HANPP map presented as Fig. 1b in Haberl et al. (2007, p. 12,943). We then calculate the ratio of HANPP on each country's territory to the embodied HANPP associated with its population's biomass consumption (Fig. 2b). We also calculate the ratio between the embodied HANPP associated with each country's international trade and the global total of embodied HANPP related to international trade (Fig. 2c and Table 1 below).

Table 1. The ten largest (a) net-exporting and (b) net-importing countries of embodied HANPP in the year 2000.

(a) Exports	Embodied HANPP transfer	% of total net-exported embodied HANPP
	[TgC/year]	
United States of Amrica	411.1	23%
Australia	265.1	15%
Argentina	253.1	14%
Brazil	211.7	12%
Canada	188.9	11%
Thailand	67.9	4%
Kazakhstan	54.1	3%
Ukraine	30.7	2%
Malaysia	25.3	1%
France	23.2	1%
(b) Imports	**Embodied HANPP transfer**	**% of total net-imported embodied HANPP**
	[TgC/year]	
Japan	234.0	13%
China	146.8	8%
Netherlands	105.6	6%
Korea, Republic of	101.6	6%
Mexico	90.9	5%
Italy	84.2	5%
Belgium-Luxembourg	78.6	4%
Germany	74.8	4%
United Kingdom	64.5	4%
Spain	64.5	4%

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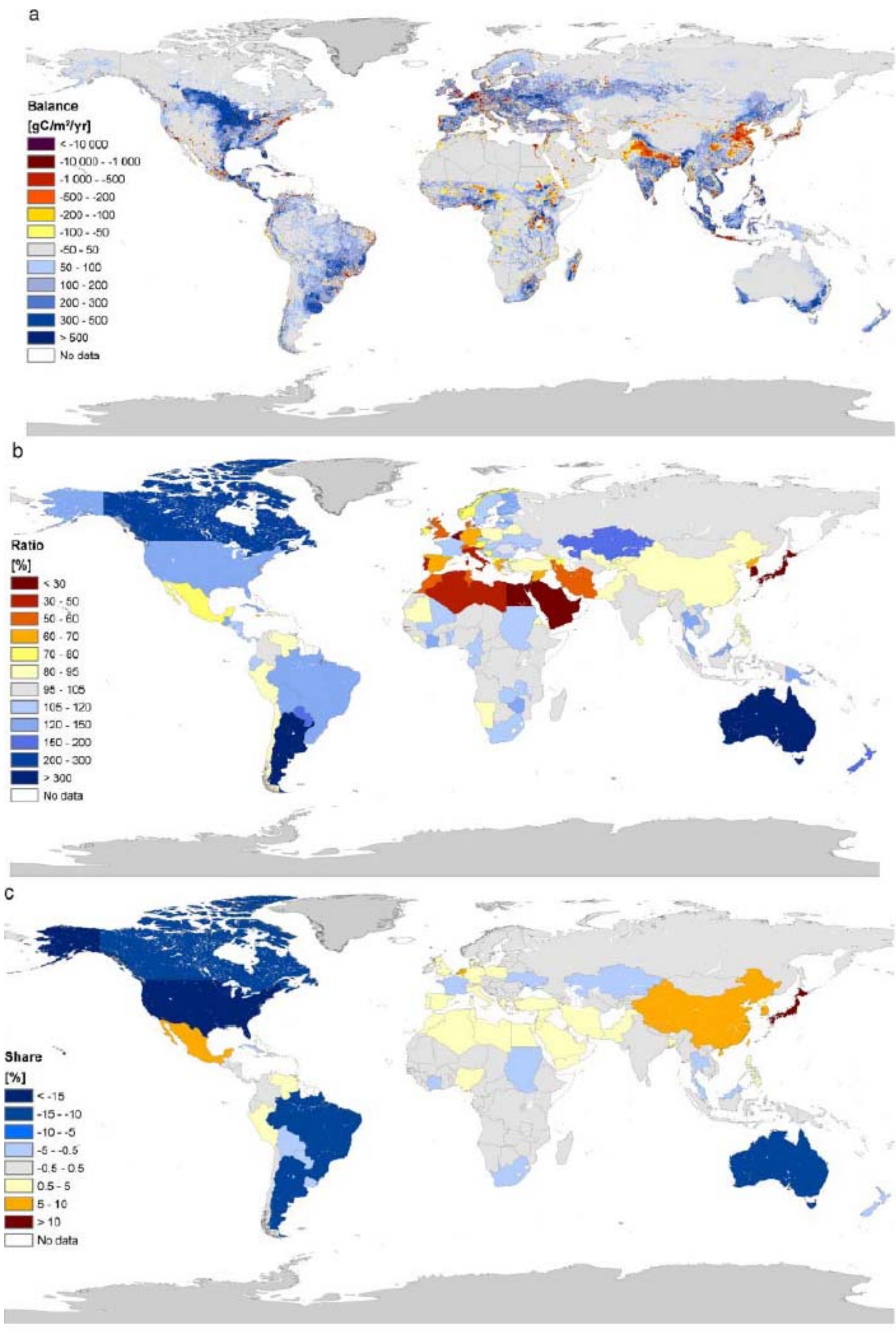

Fig. 2. The spatial disconnect between global biomass production and consumption. For each grid cell, map (a) shows the difference between HANPP on its terrestrial area and the embodied HANPP associated with the consumption of biomass-derived products of humans living therein. Map (b) displays the ratio of HANPP on each country's territory to the embodied HANPP associated with the biomass consumption of its population. Map (c) presents each country's share in the global provision and consumption of trade-related embodied HANPP (100% corresponds to the internationally transferred embodied HANPP of 1.7 PgC/year). Cold colours (shades of blue) mark the grid cells (a) or countries (b and c) where HANPP exceeds the consumption of embodied HANPP (net-producing areas). Warm colours (yellow, orange and red) identify the opposite pattern (net-consuming areas).

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3. Results

Fig.1 displays the global pattern of embodiedHANPP consumption at a resolution of 5 min, illustrating the concentration of embodied HANPP consumption in urban centres and regions of high population density. This map is conceptually similar to that of Imhoff et al. (2004), but uses a coherent database and thus allows for consistent comparison with the HANPP map for the same year published by Haberl et al. (2007).

Fig. 2a depicts a grid cell-level balance of HANPP and the HANPP embodied in the biomass consumed by humans living in each grid cell. Cold (blue) grid cells indicate areas where HANPP is larger than the consumption of embodied HANPP. These are net-producing areas; that is, areas that provide a net flow of biomass to the world market. Warm (red) areas indicate net-consuming areas in which the consumption of embodied NPP is larger than the HANPP related to domestic biomass harvest. Net-consuming areas are much smaller than net-producing areas, reflecting the increasing concentration of world population in urban centres (Millenium Ecosystem Assessment, 2005; UN, 2006) in which embodied HANPP flows per unit area exceed natural NPP often by orders of magnitude (Imhoff et al., 2004).

On the global level, almost half of the earth's surface (42% or 56 million km^2) can be considered as unbalanced, with HANPP and embodied HANPP consumption diverging by more than 5%. The remaining 77 million km2 is mostly situated in unfavourable climate with almost no land use (Erb et al., 2007) and very low population densities. Net-producing grid cells occupy 45 million km^2, consuming grid cells 11 million km2. This means that embodied HANPP gets spatially concentrated by a factor 4 on the global average between netproducing and net-consuming regions. This factor is highly variable among the world regions, being as low as 1.7 for import-dependent North Africa and West Asia (NAWA), and as high as 19.4 for export- oriented Australia and Oceania. The global imbalance of producing and consuming areas is offset by a virtual transfer of embodied HANPP associated with the trade of biomass-related products. The location and size of net-producing and net-consuming regions imply that, even assuming the shortest possible transfer distances, the flow of embodied HANPP bridges considerable distances. Globally, HANPP equals the consumption of embodied HANPP, but the large imbalance of HANPP and consumption of embodied HANPP found at the grid level is also reflected at the national level. This is illustrated by Fig. 2b which maps the ratio of HANPP and consumption of embodied HANPP on the country level. Sparsely populated, yet highly productive New World countries (the Americas and Australia) tend to be netproducing areas. In some cases, HANPP even exceeds the consumption of embodied HANPP two to three-fold. Most Old World countries (Europe, Asia, North Africa) are mostly net-consuming areas. Large regions – Russia and most developing countries in Africa, South, South-East and East Asia – do so far not yet have a significant flow of HANPP embodied in their net biomass trade. However, in some of these countries there is a considerable imbalance of net-producing and net-consuming areas within their territory (e.g., India, Fig. 2a). Fig 2c, depicting the share of net-producing and net-consuming countries in global transfers of embodied HANPP, indicates that the flow of embodied HANPP is dominated by a fewcountries. Table 1 shows that only ten countries, principally located in the Americas and Oceania, supply 86% of the total HANPP embodied in global biomass exports. Ten other countries,mainly in Eastern Asia and Europe, consume 59% of the global embodied HANPP provided by other nations.

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Table 2. Global patterns in the transfer of embodied HANPP in the year 2000.[a]

Country groups [b]	Three most important countries [c]	Area	Population	Population density	HANPP		Net trade [e]		Multiplier [f]	Embodied HANPP transfer		Consumption of embodied HANPP	Embodied HANPP transfer/embodied HANPP consumption
		[10^6 km]	[10^6]	[cap/km^2]	[TgC/year]	[%]d	[TgC/year]	[%]	[factor]	[TgC/year]	[%]	[TgC/year]	[%]
LD-I exporters	USA, Australia, Canada	48.9	525	11	3239	16%	-128	61%	7.5	-959	54%	2281	-42%
LD-D exporters	Argentina, Brazil, Paraguay	27.2	500	18	2890	16%	-37	18%	16.4	-606	34%	2285	-27%
HD-D exporters	Thailand, Malaysia, Cuba	5.0	531	107	1513	31%	-18	9%	7.8	-140	8%	1373	-10%
HD-I exporters	Ukraine, France, Hungary	1.7	158	96	535	54%	-19	9%	3.6	-68	4%	468	-15%
Total net exporters		82.8	1714	21	8177	18%	-202	97%	8.8	-1773	100%	6407	-28%
HD-I importers	Japan, Netherlands, S. Korea	3.1	557	180	812	45%	101	50%	8.9	903	54%	1716	53%
NAWA importers	Egypt, Iran, S. Arabia	11.5	371	32	398	37%	41	20%	8.8	361	21%	759	48%
HD-D importers	China, Mexico, Bangladesh	19.5	3073	158	4025	45%	48	24%	7.3	351	21%	4379	8%
LD-D importers	Venezuela, Peru, Chile	12.7	207	16	826	10%	4	2%	12.3	49	3%	875	6%
LD-I importers	Belarus, Norway, Uzbekistan	1.3	51	38	99	22%	2	1%	9.5	19	1%	118	16%
Total net importers		48.1	4258	89	6160	30%	196	97%	8.6	1683	100%	7847	21%

[a] The analysis is based on data for 143 countries. The remaining countries (1.2% of world population) are excluded due to insufficient data availability. Deviations between the global sum of net imports and net exports are due to flaws in international trade matrices and the exclusion of countries with insufficient data. For a list of countries see supporting Table S1 in the online supporting material.

[b] The threshold between low and high population density (LD, HD) is set at 50 inhabitants per km2. I…industrialized countries and transition markets, D…developing countries (for details see Haberl et al., 2007 and the supporting online material). North African and Western Asia (NAWA) countries are treated separately to reflect their specific trade pattern (Fig. 1b).

[c] Countries ranked by contribution to the international transfer of embodied HANPP.

[d] HANPP as percent of NPP_0.

[e] Net trade refers to import minus export of biomass products.

[f] Multipliers represent the upstream requirements in gC per gC of traded product. For details see text.

4. Discussion

The exchange of embodied HANPP between producing and consuming regions is dominated by flows from countries with low population density to countries with high population density, not from developing to industrialized countries. On one hand, this should not be surprising because it is trade's intrinsic function to overcome supply scarcities. On the other hand, the finding is counterintuitive in the light of results indicating that industrialized countries increasingly rely on raw materials from developing regions (Liu et al., 2007; Ciccantell, 1998). Our results suggest that the picture is complex and heterogeneous. Of the international net flow of embodied HANPP of 1.7 PgC/year, the largest fraction (88%) is supplied by low-density countries with an average population density of 14 inhabitants per km^2, including both industrialized and developing countries. 75% of the international net flow of embodied HANPP is consumed in highdensity countries with an average population density of 161 km^2 (Table 2). Currently, industrialized countries dominate both groups of countries, for the international net-production (58%) and netconsumption (55%) of the embodied HANPP flows, but developing countries contribute significantly to this exchange as well (Table 2).

Developing high-density countries, including China and India, are inhabited by half of the world's population and consume roughly one fifth of the international net flow of embodied HANPP. These countries, however, are still almost self-sufficient in total net amounts, obtaining only 8% of their embodied HANPP consumption from outside their territories (Fig. 2b). Currently, HANPP is particularly high in this region, 38% and 73% of potential NPP in China and India, respectively (Haberl et al., 2007). Another fifth of the global embodied HANPP transfer is consumed in North Africa andWestern Asia (NAWA region). Countries of this region, mostly oil exporting desert states, are a special case. They are sparsely populated, but most of their territory is arid and unproductive. HANPP in this region amounts to 42% (Haberl et al., 2007). These countries heavily rely on biomass imports, thus the consumption of embodied HANPP exceeds the HANPP on their territories by a factor of two (Table 2). Population growth (Lutz et al., 2004) and changes in dietary habits (Myers and Kent, 2003) in these country groups are likely to outpace their capacity to meet their growing demand on their own territory and to exacerbate their net-import dependency, in particular in the case of India. At the same time, many industrial countries are currently implementing vigorous policies to substitute biomass for fossil energy, thus also driving up biomass demand (Goldemberg, 2000; Fischer et al., 2009; Howarth and Bringezu, 2009). This will likely increase the biomass imports of high-density industrialized countries and may reduce exports from low-density industrialized countries. Such developments could boost agricultural prices and jeopardize the ability of import-dependent poor countries to maintain their food supply at reasonable costs, in particular if oil prices rise, as this would imply elevated costs of transportation and agro-chemicals, further adding to their vulnerability against climate fluctuations (IPCC, 2007).

Because strategies of intensification and expansion of land use can be associated with unfavourable consequences for ecosystem services other than provisioning services (Millenium Ecosystem Assessment, 2005; Foley et al., 2005), it will be decisive how and where rising biomass demand will be met. The prevalence of increasingly spatially separated interactions of society and ecosystems, fostered by trends in urbanization and global trade, poses a challenge for environmental management. As market prices neglect impacts of biomass production on other than provisioning ecosystem services, economic benefits from agriculture and forestry may not match the associated loss in ecosystem services (Daily et al., 1997; Costanza et al., 1997; Naylor et al., 2005). Thus, markets alone cannot be expected to regulate and optimize the global exchange processes analyzed in this paper.

Our results reveal that biomass trade is a major driver of biogeochemical cycles on a global scale. Global cross-border net flows of embodied HANPP amount to 1.7 PgC/year or 12% of global HANPP (Table 2). While only a fraction of this carbon flow actually crosses national borders in form of traded biomass (see Ciais et al., 2007, 2008), the magnitude nevertheless seems significant compared with global carbon emissions from industrial processes (c.7.6 PgC/year) or the current total annual global net emissions of carbon stemming from land use change (mostly deforestation) of 1.5 PgC/year (Canadell et al., 2007). Calculations of net flows –which we here present because they allow to quantify and visualize discrepancies between production and consumption – are, however, not sufficient to capture the full global extent of this process. Countries usually import and export biomass at the same time, the total global flow of internationally traded biomass is therefore considerably larger than the net flow. In the year 2000, the global volume of international biomass trade (imports = exports) amounted to 0.46 PgC/year (FAO, 2005), an equivalent of 3% of the total HANPP of 15.6 PgC/year (Haberl et al., 2007). This seemingly small flow, however, is associated with upstream flows of embodied HANPP of 3.0 PgC/year or one fifth of total global HANPP. Furthermore, international biomass trade has grown steadily over the last 40 years (Fig. 3), despite losing economic significance compared to the total volume of globally traded goods measured in monetary units (United Nations Statistical Division, 2007), suggesting that the spatial separation between production and consumption will be exacerbated in the coming decades.

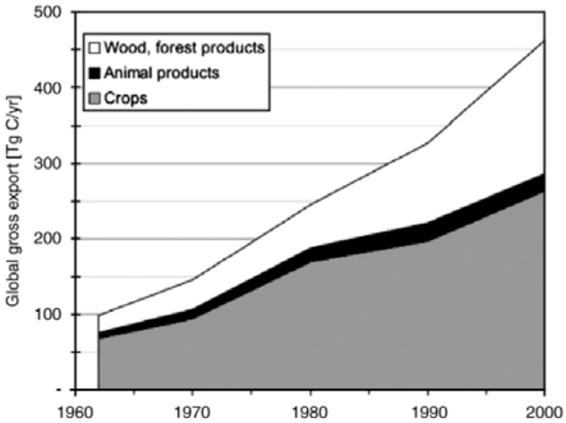

Fig. 3. Global biomass exports 1962–2000. FAO data (FAO, 2005) are converted to carbon contents using standard tables (Haberl et al., 2007). Aggregate export grows by a factor of 4.7 from 1962 to 2000, crops by a factor of 3.9, animal products by a factor of 2.8 and wood and forest products by a factor of 7.8.

The high degree of international interdependence resulting from the separation of producing and consuming systems poses a major challenge to human societies. Our analysis of net flows of embodied HANPP suggests that it is highly important to properly understand spatial aspects of socio-ecological interactions in order to tackle current sustainability challenges. Accounts that trace biomass flows from the place of harvest to the place of consumption – an obvious next step that would follow the research presented here – could provide further insights. Establishing such databases requires significant extensions of currently available data on global socioeconomic metabolism (Ayres and Simonis, 1994; Fischer-Kowalski and Haberl, 2007), in particular of material and energy flows within and between countries. Analyses whether and how trade can enhance biomass use while reducing the impacts on ecosystems, or whether it simply shifts the environmental burden to a distant location and

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withdraws it from environmental legislation (Munksgaard et al., 2005; Naylor et al., 2005) will be decisive in the context of sustainability. Integrated measures that are able to tackle the within-scalar and cross-scalar influences and outcomes of the coupled socio-ecological systems, with regard to drivers, feedbacks, thresholds and resilience are especially required, as developments as well as failures in one region increasingly have effects on far distant regions. Our results underline the need to monitor and sustainably manage supply and demand of the products of ecosystems at the global level.

Acknowledgements

The authors are grateful to A. Bondeau, V. Gaube, S. Gingrich, C. Plutzar, J. Steinberger and M. Fischer-Kowalski, to the reviewers of earlier versions of the manuscript, and acknowledge funding by the Austrian Science Fund Projects P20812-G11 and P21012-G11. This study contributes to the Global Land Project (www.globallandproject.org) and to A Long-Term Biodiversity, Ecosystem and Awareness Research Network (ALTER-Net), a network of excellence within the EU's FP6.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolecon.2009.06.025.

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