Using embodied HANPP to analyze teleconnections in the global land system: Conceptual considerations

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Abstract

In our rapidly globalizing world economy activities in one region have increasingly important effects on ecological, economic or social processes elsewhere, an effect which we here denote as 'teleconnections' between different regions. Biomass trade, one of the causes behind such teleconnections, is currently growing exponentially. Integrated analyses of changes in the global land system are high on the agenda of sustainability science, but a methodological framework for a consistent allocation of environmental burdens related to the consumption and production of biomass between regions has not been put forth to date. The concept of the 'embodied human appropriation of net primary production' (abbreviated 'embodied HANPP' or 'eHANPP') allows for the assessment of the 'upstream' effects on ecosystem energetics associated with a particular level of biomass consumption or with a given biomass-based product. This concept is based on HANPP and its two components: (1) productivity changes resulting from land conversion (ΔNPP_{LC}), and (2) harvest of biomass in ecosystems (NPP_h). HANPP, defined as the sum of ΔNPP_{LC} and NPP_h in any given territory, is indicative of the intensity with which humans use the land for their purposes. eHANPP is defined as the NPP appropriated in the course of biomass production, encompassing losses along the production chain as well as productivity changes induced through land conversion or harvest. By making the pressure exerted on ecosystems associated with imports and exports visible, eHANPP allows for the analysis of teleconnections between producing and consuming regions. This article puts forward the eHANPP concept, illustrates its utility for integrated socioecological land-change research based on top-down data on global HANPP and biomass consumption, and discusses the possibilities and challenges related to its quantification in bottom-up approaches.

Keywords

Human appropriation of net primary production, embodied HANPP, biomass flows, land system change.

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Introduction

Global land use is a pervasive driver of global environmental change. It contributes to the current rapid biodiversity loss, to the erosion of the ability of terrestrial ecosystems to deliver vital services to human society as well as to net releases of carbon dioxide into the atmosphere (Millennium Ecosystem Assessment, 2005; Field et al., 2004). Understanding the drivers of land-use change is therefore high on the agenda of global change and sustainability research (Geist & Lambin, 2002; Lambin & Geist, 2006; Turner et al., 2007).

In our rapidly globalizing world economy, land use is to an increasing extent being driven by activities occuring somewhere else. Socioeconomic activities – above all, patterns in production and consumption – have impacts on land systems that are more and more reaching beyond the boundary of the place where they occur (Grenz et al., 2007; Turner et al., 2007). Products derived from using the land are often not consumed where they are produced. The dependence of urban areas on their rural hinterland and the trade of biomass-based products between countries or even continents are particularly consequential in this regard. Both intra- and international biomass trade can result in causal connections between different places and regions in the global land system (Erb, 2004; Erb et al., 2009).

This phenomenon has been denoted as 'teleconnections', a notion that first emerged in the atmospheric sciences, where it denotes causal links between different weather systems (Wallace & Gutzler, 1981). Teleconnections have been defined as "the correlation between specific planetary processes in one region of the world to distant and seemingly unconnected regions elsewhere" (Steffen, 2006, p. 156). Such teleconnections can be caused by different socioeconomic or biophysical processes and feedbacks. Trade, on which we focus here, is only one of those. However, trade has been growing exponentially for at least four decades (Figure 1), suggesting that its importance in causing teleconnections is growing rapidly. Since the early 1960s, the volume of global trade of biomass products has increased by a factor of 6. Currently, global exports of biomass amount to 1.5 Gt fresh weight per year (1 Gt = 10^9 metric tons). Not only the total amount of biomass trade, but also the share of all biomass consumed by humans globally that is traded internationally is surging and has almost tripled since 1962 (Krausmann et al., 2008).

Moreover, urbanization is progressing rapidly across the globe: while 47% of the world population lived in cities in 2000, the share of city-dwellers is expected to rise to 70% in 2050 (UN, 2008). Urbanization grows rapidly during transitions from agrarian to industrial society, supported by rising agricultural yields, agricultural labour efficiency and efficient, far-reaching transport systems. These changes have led to the current situation where urban systems depend on resources from large, often far-distant hinterlands and pressures on ecosystem that result from biomass production in urban areas are largely a result of the consumption of urban areas (Krausmann et al., 2003; Haberl & Krausmann, 2007).

There is a growing need to understand the teleconnections between producing and consuming regions in order to foster sustainability, in particular as globalization is processing quickly and distances bridged by trade flows are increasing rapidly (van den Bergh & Verbruggen, 1999; Muradian et al., 2002; Muradian & Martinez-Alier, 2001). As the spatial separation of production and consumption progresses, the causal linkages between socioeconomic drivers and ecological as well as social impacts become increasingly opaque. The result is a high degree of international interdependence, with unknown consequences for the resilience of socioecological systems (Erb et al., 2009). The spatial disconnect between drivers and their impacts may contribute to ecological distribution conflicts (Martinez-Alier, 2002). Environmental burdens may be shifted outside the realm of national environmental legislation (Munksgaard et al., 2005).

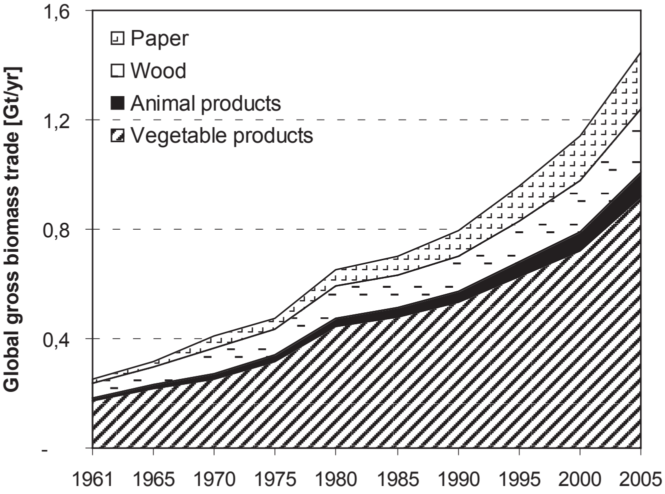

Figure 1: *Growth in the global gross trade volume (sum of exports of all countries = sum of imports of all countries) of biomass (fresh weight). 1 Gt = 1 Gigaton = 10^9 t = 1 Petagram = 10^{15} g. Data source: FAO (2008).*

These considerations suggest that the need for a development of tools and conceptual frameworks which allow for systematic, comprehensive (e.g. sensitive to problem shifts) analyses of the complex causalities between drivers and impacts along production-consumption chains. One such methodological framework is provided by the concept of 'virtual water' flows associated with biomass trade (Allan, 1998; Hoekstra & Hung, 2005), sometimes also denoted as the 'water footprint' of biomass-based products (Gerbens-Leenes et al., 2009). This concept allows to evaluate the impacts of biomass consumption on the water balance of the regions where the biomass is being produced.

We here discuss a related concept that focuses on the impacts of biomass consumption on ecosystem energetics: the 'embodied human appropriation of net primary production' (embodied HANPP or eHANPP). We propose that eHANPP is a tool to better understand trade-related teleconnections in the global land system that helps in analyzing impacts not or not fully captured by the water footprint approach. We see these two concepts as mutually reinforcing and complimentary. We here show how data on global HANPP (Haberl et al., 2007) can be combined with data on global socioeconomic biomass flows (Krausmann et al., 2008) to calculate the amount of HANPP caused during the production of the amount of biomass consumed in countries (that is, a national eHANPP balance) in a top-down manner. We also discuss how bottom-up methods could be developed to assess the eHANPP resulting from the production of products that are based on agricultural or forest biomass.

The embodied HANPP concept and its possible applications

The term 'embodied HANPP' is introduced here to describe the amount of HANPP associated with a given level of biomass consumption or with a specific product originating from biomass. It is based upon the HANPP concept as proposed two decades ago (Vitousek et al., 1986; Vitousek et al., 1997) as an indicator of human domination of ecosystems. Since then, HANPP has proven its value as a measure of socioecological conditions in the land system that helps in integrating socioeconomic and ecological perspectives (Krausmann et al., 2009). Net primary production (NPP) is the net amount of biomass produced by green plants through photosynthesis in a defined area per unit of time (e.g., per year). HANPP is a measure of the extent to which human activities affect NPP and its availability in the ecosystem as a source of nutritional energy and other ecosystem processes (Haberl, 1997).

HANPP is a composite measure of the impacts on biomass energy flows in terrestrial ecosystems resulting from biomass harvest (NPP_h) and productivity changes due to land conversion (ΔNPP_{LC}), i.e. the effects of land use on NPP due to replacement of natural ecosystems with agro-ecosystems, degradation, soil sealing or other processes. HANPP thereby measures the land-use induced changes in the yearly availability of biomass energy for all heterotrophic organisms, i.e. food energy-consuming organisms, as opposed to autotrophic organisms that are capable of photosynthesis. HANPP and its components are indicative of the quality of land management. HANPP influences biodiversity (Wright, 1990; Haberl et al., 2005), biogeochemical cycles (Steffen et al., 2004), and the water cycle (Gerten et al., 2008). HANPP is defined as $HANPP = NPP_0 - NPP_t$. NPP_0 denotes the NPP of potential vegetation and NPP_t the NPP remaining in ecosystems after harvest (Haberl et al. 2007). NPP_t can be calculated by subtracting NPP_h – harvest of NPP, including biomass destroyed during harvest – from NPP_{act}; that is, the NPP of the currently prevailing vegetation. The difference between NPP_{act} and NPP_0 is denoted as ΔNPP_{LC}; that is, the change in NPP resulting from land conversion.

Embodied HANPP is defined as the total HANPP associated with the production of a raw material, an intermediate or a final product. Its calculation takes the whole production chain into account, including both biomass flows occurring during agricultural or forest production and changes in NPP resulting from land conversion (Figure 2).

The following upstream biomass flows are included in eHANPP accounts: (a) changes in the productivity of ecosystems, denoted as ΔNPP_{LC} (Haberl et al., 2007), (b) by-flows of harvest, such as plant parts destroyed during harvest but not recovered (e.g. roots or agricultural residues, or felling losses in forestry), which are included in HANPP accounts because they are heavily affected by the harvest event, and (c) losses in the production chain

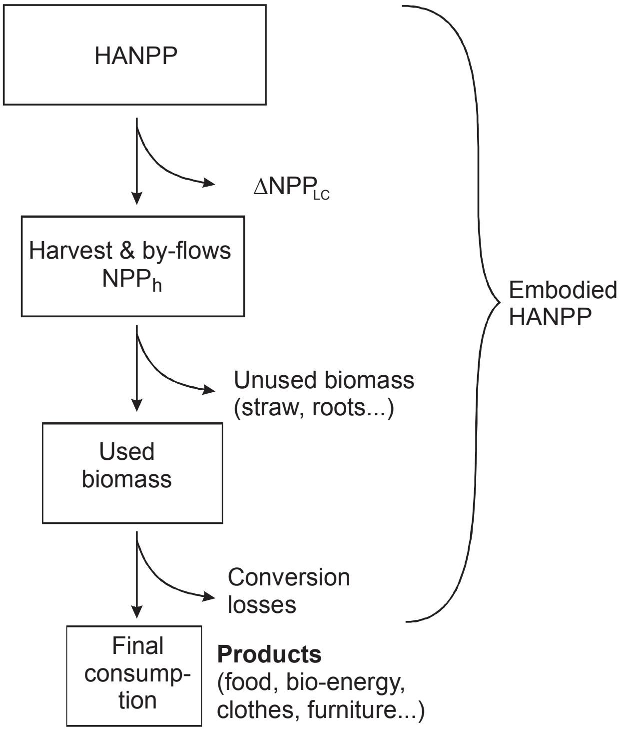

Figure 2: *Idealized representation of the embodied HANPP concept. The production of biomass implies changes in ecological productivity (ΔNPP_{LC}). Not all biomass is recovered (residues, by-flows) and biomass is lost in conversion processes.*

between primary biomass harvested (e.g., cereals, vegetables or tree trunks) and final biomass products (e.g., food or biofuels). The amount of NPP appropriated during production is substantially larger than the final consumption of biomass. On the global average, for each ton of final biomass product (measured as dry matter), 3.1 tons of dry matter biomass are harvested, 1.7 tons are lost or destroyed during harvest (Krausmann et al., 2008). In addition, each ton of final biomass consumption is associated with a ΔNPP_{LC} of 3.2 tons of NPP (Erb et al., 2009).

The eHANPP concept can be applied to compare different products with respect to the pressure on ecosystems associated with their production. An example of a particularly relevant comparison of biomass products is the analysis of different bioenergy carriers, such as liquid biofuels, fuel wood or other solid bioenergy carriers derived from residues and waste. The use of bioenergy is propagated widely as a measure to mitigate climate change. Biofuel demand is increasing rapidly due to political interventions such as subsidies (FAO, 2008). For example, the European Union has set a target for a compulsory share of 10% for energy from renewable sources in transport by 2020, also driving up demand for liquid biofuels (Eickhout et al., 2008). The pressure on ecosystems associated with the production of one energy unit of bioenergy is subject to large variation, depending on the type of biomass fuel and process chain involved in the production of the related bioenergy carrier. eHANPP would give an indication of the pressure associated with different bioenergy pathways and would allow to trace imported biofuels back to their regions of origin, if calculated appropriately.

Furthermore, eHANPP accounts would enable researchers to determine the 'energy return on energy appropriation' (energy produced per unit of eHANPP) for different biomass products, in particular biofuels. eHANPP accounts could thus add a new, relevant dimension to sustainability indicators for biomass production and trade (Haberl & Erb, 2006), in addition to accounting frameworks that quantify embodied carbon flows (Searchinger et al., 2008; Fargione et al., 2008; Marland & Schlamadinger, 2002; Schlamadinger & Marland, 1999) or 'virtual' water flows (Gerbens-Leenes et al., 2009; Hoekstra & Hung, 2005).

In addition to such cross-product comparisons, eHANPP is also applicable in identifying the environmental pressures associated with biomass consumption on different levels. These pressures depend strongly on the location of biomass production due to the fact that HANPP shows large spatial variation across the globe (Haberl et al., 2007) and is co-determined by natural factors such as climate, soil productivity or land forms as well as by socioeconomic factors such as population density, trade, agricultural technology, energy use, diets or economic growth (Krausmann et al., 2009). As Figure 3 shows, HANPP ranges between 11% and 63% in different large world regions. While ΔNPP_{LC} plays an important role in regions such as East and Southeast Europe and Southeast Asia, NPP_h dominates the total HANPP in regions such as West Europe. Differences in yields, productivities of livestock systems, biomass conversion efficiencies, diets and other biomass consumption patterns between regions are large, thereby causing considerable differences in the ratio between eHANPP and final biomass consumption (Erb et al., 2009). eHANPP can be used to identify and allocate the pressures on ecosystems associated with biomass consumption in different countries or regions.

The following sections discuss two calculation approaches. According to the underlying procedures and the data on which they rely, these approaches can be identified as a top-down and a bottom-up approach to the calculation of eHANPP.

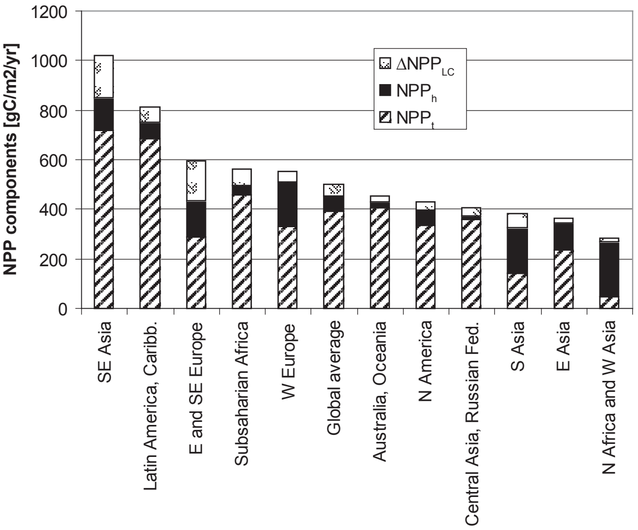

Figure 3: *Regional breakdown of NPP components (excluding human-induced fires) to 11 world regions and global average. HANPP is defined as the sum of* NPP_h *(harvest) and* ΔNPP_{LC} *(productivity change resulting from land conversion; see text).* NPP_t *is the amount of NPP remaining in ecosystems after harvest.* NPP_h *data exclude human-induced fires. HANPP calculated as a percentage of* NPP_0 *ranges from only 11% in Australia and Oceania to 63% in South Asia. Data source: Haberl et al. (2007).*

A top-down approach to calculate embodied HANPP

eHANPP accounts derived from a top-down approach can be applied to analyze the upstream HANPP associated with trade. For each country, domestic consumption of eHANPP can be calculated as the sum of HANPP on the national territory and HANPP embodied in biomass imports minus HANPP embodied in exports. The amount of HANPP embodied in trade is calculated by multiplying the mass of internationally traded biomass products with upstream multipliers. These are derived from data on global biomass flows and HANPP for individual countries (Haberl et al., 2007; Krausmann et al., 2008) and are calculated at the national level as the ratio of biomass outputs of the socioeconomic system (food, fibre, timber, and biofuels for final consumption, including exports) to all NPP inputs required to produce them. The latter includes the mass flow of primary crops, used crop residues, biomass harvested from grassland and grazed biomass, wood removals, unrecovered crop residues and felling losses, belowground biomass of harvested primary crops and felled trees, imported biomass products, ΔNPP_{LC} on agricultural and forestry lands, and ΔNPP_{LC} related to the infrastructure required for biomass production and trade. As biomass accounts for 40% of global resource extraction (Schandl & Eisenmenger, 2006), ΔNPP_{LC} related to the infrastructure required for biomass production and trade was set to be 40% of total national ΔNPP_{LC} resulting from rural infrastructure. Data on national ΔNPP_{LC} were taken from Haberl et al. (2007).

While national-level multipliers for each country were used for the calculation of eHANPP flows associated with biomass exports, the weighted average of the multipliers of all net-exporting countries was used in calculating the eHANPP of imports. More accurate results could be derived on the basis of bilateral trade matrices, but such an approach was beyond the scope of the work presented here due to the excessive amount of data handling it would have required.

Table 1 shows the results of the embodied HANPP

Table 1: *The impact of trade on national HANPP in selected countries: HANPP denotes HANPP on the national territory; eHANPP denotes the eHANPP associated to domestic consumption; HANPP embodied in trade is equal to the difference between HANPP and eHANPP. All data refer to the year 2000. Sources: Population density and income (GDP in const. 2,000 US$ per capita and year): FAO (2008) and World Bank (2006); HANPP: Erb et al. (2009), see text. HANPP values and biomass flows are given as yearly flows of dry matter biomass (1 Mt = 10^6 t = 10^{12} g = 1 Tg).*

Country type	Country name	Population density	Income	HANPP	eHANPP	Biomass net trade	HANPP embodied in trade	eHANPP per unit of biomass net trade
		[cap/km²]	[US$/cap/yr]	[Mt / yr]	[Mt /yr]	[Mt / yr]	[Mt / yr]	Factor
Low density industrial	USA	29	34,477	2,830	2,008	-92	-822	8.9
	Australia	2	20,883	708	177	-36	-530	14.7
Low density developing	Argentina	13	7,675	696	190	-44	-506	11.5
	Brazil	20	3,531	2,274	1,851	-23	-423	18.4
High density industrial	Japan	336	36,583	113	581	78	468	6.0
	Italy	191	19,074	168	336	26	168	6.6
High density developing	India	307	456	2,512	2,518	2	7	4.2
	China	134	935	2,667	2,960	45	294	6.5
Arid low density developing	Egypt	68	1,471	38	152	13	113	9.0
	Iran	43	1,440	157	264	12	95	8.0

calculation for selected countries. It compares HANPP (i.e., HANPP on the national territory) and eHANPP (i.e., the eHANPP associated to domestic consumption) in five types of countries. Based on insights from previous work on the influence of socio-economic and bio-geographic factors on HANPP (Krausmann et al., 2009), we have chosen countries according to differences in population density and development status. As natural factors, in particular the aridity of a region, are also found to be decisive, a fifth group with examples of arid countries is included in Table 1.

Argentina and Brazil, both low-density developing countries, and the USA and Australia, both low-density industrial countries, are characterized by large net exports of eHANPP. In other words, the HANPP on their territories is much larger than eHANPP associated with their national biomass consumption, +23% and +41% for Brazil and the USA, respectively. For Australia and Argentina, HANPP on their territory even exceeds eHANPP of national biomass consumption 3 to 4-fold.

In contrast, densely populated countries tend to be net importers of embodied HANPP. Table 1 illustrates that this is particularly the case for industrialized countries. In Japan and Italy, both characterized by a population density at least four times larger than the world average of approximately 50 inhabitants per km², only a fraction of the eHANPP associated with national consumption originates from their own territories (19% and 50%, respectively), the remainder is covered by net imports. Thus, the global HANPP, i.e. the global pressure on ecosystems associated with the consumption level of these countries, is much larger than an account of the HANPP on their national territory would suggest.

Although densely populated developing countries such as China or India also appear to be net importers of eHANPP, the contribution of imports to national eHANPP is still modest. Table 1 shows that, for example in India, HANPP and eHANPP are almost identical, and China's net imports of eHANPP is only 9% of the eHANPP associated with the consumption of biomass within its territory.

Arid countries, in contrast, tend to be massive net biomass importers despite being sparsely populated and their eHANPP considerably exceeds the HANPP on their territory. The Islamic Republic of Iran, for example, covers only two thirds of its eHANPP consumption by domestic biomass production. In Egypt, only one quarter of the eHANPP resulting from domestic biomass consumption originates from domestic land use, the lion's share occurs outside its territory.

Table 1 also reveals large discrepancies across nations in the amount of HANPP resulting from the consumption of one unit of biomass. In India, for example, eHANPP per ton of dry matter biomass consumed per year amounts to only 4.2 tons dry matter. This factor can be as large as 18.4 in Brazil and 14.7 in Australia. Most other countries in the database (not shown) have embodied HANPP factors that fall between these extreme values. This highlights the huge differences in diets (vegetarian versus animal products), biomass conversion and land use efficiencies prevailing globally.

The examples in Table 1 indicate that the differences between HANPP on national territory and eHANPP associated with the national consumption of biomass can be substantial. In particular, industrialized regions with high population densities tend to be massive importers of eHANPP, and thus may be said to appropriate ecological services elsewhere (Millennium Ecosystem Assessment, 2005). Current energy strategies aimed at fostering the use of bioenergy in industrialized regions such as the European Union's biofuel directive (Eickhout et al., 2008), will further increase the demand for biomass imports in these countries.

Although the top-down approach to calculate eHANPP at a relatively high level of aggregation (with respect to the resolution of biomass types) which has been outlined above (see also Erb et al., 2009) seems feasible and comparatively straightforward, it entails several intricacies. One issue is related to the calculation of upstream requirements of imported products. In a first order approach, it might be legitimate to calculate eHANPP related to exports with national multipliers that account for the upstream requirements for exported biomass. Similar approaches have been shown to produce valid results in ecological footprint assessments (Lenzen & Murray, 2001; Haberl et al., 2001; Gerbens-Leenes et al., 2002; van Vuuren & Bouwman, 2005). Nevertheless, re-exports of imported goods, a phenomenon that is becoming increasingly important also for agricultural products, increases the uncertainty associated with such simplifying assumptions considerably. Likewise, calculating eHANPP flows related to imports with global average multipliers neglects differences in upstream requirements resulting from different locations of harvest and thus different land use systems.

Although theoretically feasible, the practical challenges in establishing a 'perfect' eHANPP account of imported goods more accurately are formidable, in particular due to the fact that ΔNPP_{LC} and NPP_h are location-specific as well as technology-specific, even for primary products such as wheat, and much more so for processed products. Such an analysis would require databases that track the flow of each and every ton of primary product from the cradle to the grave. The establishment of such a database would be almost infeasible due to the excessive monitoring costs and data requirements. But one can aim at reasonable approximations. One big step towards such accounts are studies that quantify the actual land demand related to biomass imports based on bilateral trade matrices (Erb, 2004; Wurtenberger et al., 2006; Moran et al., 2009). These studies provide accounts of the extent of land-use areas 'embodied' in imports, i.e. the amount of land required to produce imported biomass products. Such accounts, moving beyond simple footprint accounts that operate with global average areas (Hails et al., 2008; Monfreda et al., 2004; Wackernagel & Rees, 1996; Wackernagel et al., 2004), can in principle be combined with analyses of (national) HANPP or other indicators of land-use intensity in a rather straightforward manner. Attempts to decrease the uncertainty of such accounts, however, have to tackle substantial methodological challenges.

A bottom-up approach for calculating embodied HANPP

While aggregated accounts of domestic production, imports, and exports of biomass are the point of departure for the top-down approach, the bottom-up approach to the calculation of eHANPP is product-based. It considers the NPP appropriated across an entire production process. This is illustrated in simplified form in Figure 4 using the example of beef production. The production chain which must be reconstructed in order to calculate eHANPP in this simplified case includes biomass grazing, production of market feed on cropland as well as the infrastructure areas required for transport and conversion processes.

Methods to calculate eHANPP with such an approach are currently not available. The required production chains can get very complex if one aims at a reasonably accurate representation and can be subject to strong variation even for one and the same product. In the aforementioned example, HANPP associated with the production of beef depends on the demography of the cattle system, on production technologies, and especially on the feeding system: HANPP must not only be calculated for grazing or market feed via which livestock is fed, but also for hay or fodder derived from wastes of the food industry. Upstream requirements of domestically produced and imported feed depend strongly on the efficiency of the respective country's cropland system.

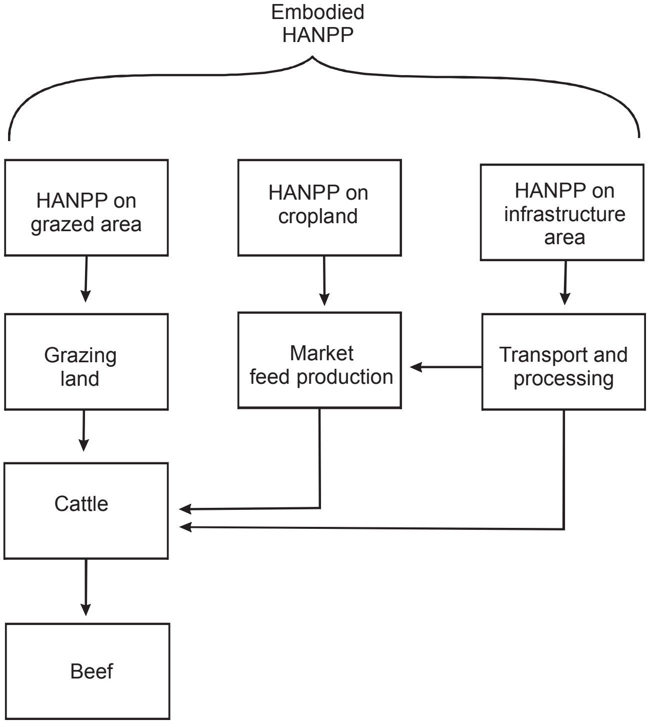

Figure 4: *Simplified representation of the embodied HANPP concept from a bottom-up perspective: Products requires 'upstream flows' that can be evaluated in a life-cycle analysis (LCA) approach.*

Beyond such difficulties, the allocation of eHANPP in multi-product production processes poses another fundamental challenge in calculating eHANPP for an individual product. Examples are the production of beef, veal, milk, bones and living animals in the case of cattle, or oil cake, oil and straw in the case of oil crops. A 'scientifically correct' solution to this challenge does not exist. We have reviewed proposed allocation strategies and discussions thereof in the LCA literature (Azapagic & Clift, 1999; Baumann & Tillman, 2004; Ekvall & Finnveden, 2001; Frischknecht, 2000; Heijungs et al., 1992; International Organisation of Standardization, 1998; Wiedmann et al., 2008, Sleeswijk et al., 1996). All the proposed approaches provide logically consistent accounting frameworks, but yield completely different results even in the cases where the underlying processes are perfectly understood and all data are available. This is due to conceptual differences according to which the allocation of inputs and environmental burdens to products is organized. The following allocation principles can be discerned:

1. All inputs are allocated to one product assumed to be the most important product of a process. In the case of the cattle system this might be meat. This so-called 'arbitrary numerical distribution' approach (Sleeswijk et al., 1996) is most often only used as a first approximation in 'screening LCAs' (Huppes, 1994; Running, 1994) and may lead to an overestimation of inputs for the dominant product.
2. For each of the different outputs (i.e. products or even services) of a production process it is possible to calculate their respective shares in the total economic value of all outputs of that process. The inputs are then allocated using these ratios. Some authors (e.g. Huppes, 1994) see this as a way of quantifying the 'social causality' of a process where economic value is the most important driver of production (Ekvall, 1994). Despite the widely recognized criticism that this approach requires the assumption of homogeneity between prices and (physical) inputs this assumption is often used (e.g. Van der Broek et al., 2002; Fargione et al., 2008).
3. Instead of using monetary values, the allocation of inputs can be made according to the mass (kg or kg dry matter), energy or exergy content (J) of the total outputs of a process. The example of meat and bones as outputs of livestock farming illustrates that different results will be obtained depending on whether mass or energetic value is used. The advantage of this principle is that it yields stable results because physical properties of products usually change much less over time than price relations. However, the consideration of outputs in this approach is not unambiguous. A dominant output in terms of mass may actually play a subordinate role in driving production (e.g. manure in livestock farming) so that it would hardly seem sensible to allocate the according share of inputs to it even if it has some economic use.
4. Apportioned allocation is avoided by either splitting a multifunctional process into sub-processes and collecting separate data (where possible) or by expanding the system boundaries (Azapagic & Clift, 1999). The former option is seldom feasible since it requires the sub-processes to be physically completely separable, single-function processes (Ekvall & Finnveden, 2001). System expansion assumes that production processes with equivalent functions have the same environmental burdens (Kim & Dale, 2002). A co-product is accordingly ascribed the same environmental impact as the single-output process which produces that same product. Since the burdens or impacts of the single-function process are avoided by producing the product in a joint-function process, the according burdens can be deducted from the latter (Kaltschmitt et al., 1997; Azapagic & Clift, 1999). Although this method reflects the additional usefulness generated by multifunctional production processes, it can lead to an underestimation of the impact of the joint-function processes.

An intricacy related all LCA based approaches is the so-called truncation problem (Lenzen & Dey, 2000; Suh, 2004; Suh et al., 2003; Wiedmann, 2009). In principle, it is not determinable on a logical basis at which point to cut off the analysis of process chains. Here, pragmatic decisions based on issues of data availability and the expected uncertainties are central.

These methodological challenges notwithstanding, the potential usefulness of such bottom-up approaches is evident, as they would allow for the comparative analysis of different biomass products with regard to the global ecological pressure associated with their production, regardless of the place of consumption. The aforementioned analysis of biofuels through comparison of their eHANPP illustrates how useful it would be to further pursue this approach.

Outlook and conclusions: embodied HANPP and integrated socio-ecological research

Global biomass trade is growing exponentially and teleconnections between producing and consuming regions are rapidly gaining importance. In a globalizing economy, developments and changes in one region increasingly result in ecological, economic or social impacts elsewhere which may contribute to ecological distribution conflicts and unequal exchange (Martinez-Alier, 2007). For example, biofuel policies in industrialized countries have resulted in a strong growth of demand for feedstocks for first-generation biofuels (Faaij, 2008). This development has provided strong incentives in tropical countries such as Indonesia and Malaysia to embark on programmes to transform large tracts of land currently dedicated to subsistence agriculture into plantations producing palm oil for export (Schmidt et al., 2009). Urbanization is progressing rapidly; forecasts suggest that the number of city-dwellers will more than double until 2050 (UN, 2008).

These examples illustrate the need for consistent, scale-independent assessments of global environmental impacts resulting from resource use patterns as well as national or supranational policies related to resource use (e.g., agricultural or energy policies). Our analysis suggests that the redistribution of bioproductivity associated with such transitions and the teleconnections driving them can be analyzed using the eHANPP concept, taking into account the far-reaching ecological, economic and social changes implied by these developments. Conceptually similar to the virtual water approach, eHANPP can provide additional insights on the impacts of biomass production and consumption chains on ecosystem energetics, an important aspect not covered by virtual water accounts.

Using a top-down approach, we have demonstrated that the eHANPP associated with a country's trade balance can be substantial and needs to be taken into account in analyzing the global implications of biomass consumption in a country as well as the interrelation between biomass consumption and land use within a country. We have shown that the eHANPP approach is capable of providing empirical data to analyze such interrelations. Extending the presently available datasets through the use of bilateral trade matrices would be feasible but data-demanding, and would result in highly useful datasets for the analysis of the global 'footprint' caused by each country's biomass consumption. We have also discussed methodological challenges involved in calculating the eHANPP of products. Our analysis suggests that such bottom-up assessments of eHANPP based on LCA methods are feasible, but considerable conceptual and data challenges still have to be overcome for this approach to become operational. Nevertheless we feel that further work in that direction is highly important because of the ability of the eHANPP concept to empirically analyze production-consumption links and teleconnections and thereby provide a sound knowledge basis for better understanding of land-use related globalization processes.

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