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Ecological footprints and human appropriation of net primary production: a comparison

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Abstract

Human appropriation of net primary production (HANPP) and the ecological footprint (EF) are two aggregate measures to assess human societies' draw on nature. Both relate socio-economic metabolism to land use and are designed to provide insights about the sustainability of society–nature interaction. Despite these similarities, there are differences between the two concepts. This paper compares the research questions driving each approach, examines how well they manage to answer their respective questions, and discusses the utility of the results for assessing regional or global sustainability. EF appraises the total bioproductive area needed to sustain a defined society's activities, wherever these areas are located on Earth. In doing so, it accounts for three functions of ecosystems used by humans—resource supply, waste absorption, and space occupied for human infrastructure. EF is useful to identify how this demand is distributed between different groups of people. In contrast, HANPP identifies the intensity with which humans use these three functions within a defined land area. HANPP maps the intensity of societal use of ecosystems in a spatially explicit manner. In contrast to EF, HANPP does not calculate the aggregate demand of a society's consumption patterns on the global biosphere. While EF evaluates the exclusive use of a society's utilization of bioproductive area, HANPP maps the intensity of this use ('human domination') in specific regions.

Keywords: Human appropriation of net primary production (HANPP); Ecological footprint (EF); Sustainability; Socio-economic metabolism; Land use

Introduction

This paper compares two approaches that seek to establish aggregate accounts for human use of nature. The two measures, which share land use as their common denominator, are: (1) Ecological footprint (EF) and (2) human appropriation of net primary production (HANPP). Both approaches recognize the significance of surface areas for ecological processes, and relate land use and socio-economic metabolism as discussed in other papers in this special issue (Haberl et al., 2004; Krausmann et al., 2004), and are designed to further sustainability analyses of societies. Nevertheless, the two concepts investigate different types of ecological impact and accordingly provide different insights into sustainability. We start by outlining ecological primary production, a process relevant for both approaches. This will be followed by an analysis of the research questions posed by the two different concepts, leading to a comparative discussion and conclusions.

Ecological primary production and socio-economic metabolism

Life on Earth ultimately depends on solar energy.[1] In the process of photosynthesis, plants absorb solar

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[1] An exception are chemolithoautotroph micro-organisms that use chemical energy (e.g., oxidation of nitrogen or iron) for primary production.

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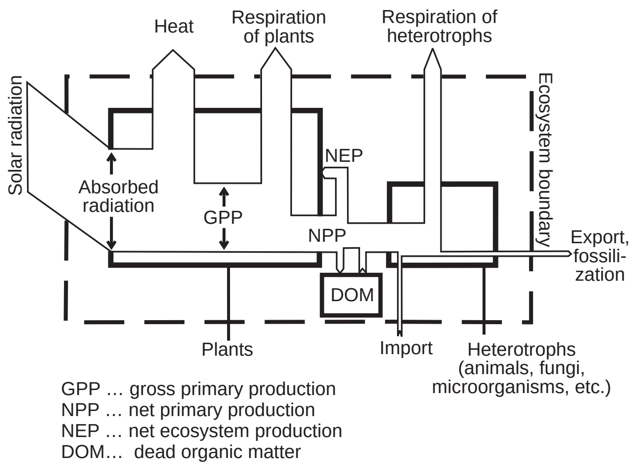

Fig. 1. Schematic diagram of the trophic-dynamic aspect of ecological energy flows.

radiation and transform it into chemically stored energy (biomass). A part of the energy is used for the plant's metabolism, the remainder may either serve to build up biomass stocks of the ecosystem or end up in heterotrophic food chains; that is, it may nourish humans, animals, fungi or micro-organisms (Odum, 1971). The gross amount of chemically stored energy produced per unit of time, usually 1 year, is denoted as gross primary production (GPP). GPP minus plant respiration—i.e., the energy needed for the plant's metabolism—is called net primary production (NPP). Fig. 1 summarizes key notions for describing the flow of trophic energy in ecosystems.

This process of ecological 'primary production' is area-dependent because photosynthesis depends on the area of the Earth that intercepts radiant solar energy. For any given place on Earth, the rate of insolation is a factor of geographical position (latitude), slope, orientation, and climate (e.g., cloud cover). The amount of incoming solar radiation that can be converted into chemical energy is not only determined by the influx of solar energy, but also by factors such as water and nutrient availability, soil quality, and plant species composition. The atmosphere absorbs and reflects about half of the total incoming solar radiation. By far the largest part of the remaining amount of energy drives atmospheric and hydrological cycles. Photosynthesis only fixes some 0.2–1.0% of the total (Schlesinger, 1997; Smil, 1992). NPP per unit of land area ranges from nearly zero in very dry or cold environments (high altitudes, polar regions, deserts, etc.) to over 3.5 kg dry matter per square metre per year in moist evergreen tropical forests (Ajtay et al., 1979).

While humans depend on ecological primary production for their food supply, the dependency of socio-economic metabolism on NPP varies among different kinds of societal organisation. Hunter-gatherers put little effort in altering ecosystems. They harvest plant or animal biomass for nutrition and manufacture of tools, clothing, etc. mostly in the form in which it occurs naturally in ecosystems, although some hunter-gatherers probably have used, and still use, fire to alter ecosystems (Butzer, 1984). Agricultural societies actively change terrestrial ecosystems in order to promote the growth of plant species they want to use, typically ones that humans can either digest or feed to their livestock (Boyden, 1992; Sieferle, 1997). While hunter-gatherers and agricultural societies both rely on NPP as their main source of primary energy (agricultural societies may also use some wind power and water power), they use this resource very differently: the latter use ecosystems with much higher intensity, and make significantly larger efforts to shape ecosystems in ways that serve their own needs more directly.[2] Such intensive land use normally entail changes in land cover. Industrial societies remain dependent on agro-ecosystems, above all with respect to food supply, but the functioning of their energy system would be impossible without non-biotic sources of energy, above all, fossil fuels (Fischer-Kowalski and Haberl, 1997; Sieferle, 1997).

If we understand sustainability as the goal of giving all humans a chance for a satisfying life, without threatening the capacity of the biosphere to remain productive and provide ecosystem services (Costanza and Farber, 2002; Daily, 1997; Munro, 1991) essential for human survival and well-being, then it is useful to consider the following three core functions of ecosystems for humans (Dunlap and Catton, 2002):

1. *Resource supply:* Land area serves as a source of inputs of socio-economic metabolism. It provides renewable and non-renewable resources such as air, water, biomass, fossil fuels, minerals, etc. Overuse may result in degradation of renewable resources or depletion of non-renewable resources. With respect to this function, biomass has a special role because its production depends on the primary production of ecosystems which implies that about 10^2–10^4 times more area is needed per unit of material or energy gained than for most non-renewable resources (Haberl and Schandl, 1999).[3]
2. *Waste absorption*: The biosphere absorbs socio-economic outputs such as wastes or emissions.

[2] This however does, not imply that the NPP of agro-ecosystems exceeds that of natural ecosystems, on the contrary: in many cases, agro-ecosystems are less productive in terms of NPP than the natural ecosystems they replace. The point is that they produce more of the kinds of biomass society can use at the expense of other kinds of biomass not useful for human purposes.

[3] Even most other renewable energy sources need considerably less area than biomass-based renewable fuels. For example, producing 1 GJ/yr wood needs 70–137 m^2, rapeseed methyl ester 212 m^2/GJ/yr, ethanol 108–217 m^2/GJ/yr, etc., whereas solar heat needs only 0.8 m^2/GJ/yr, photovoltaic cells 2.3 m^2/GJ/yr, wind power 1.1 m^2/GJ/yr, hydropower 10 m^2/GJ/yr (Stöglehner, 2003).

Table 1
A comparison of main features of the EF and HANPP. See text for details

	EF	HANPP
Research question	How big is the bioproductive area needed to uphold the socio-economic metabolism of a given population, using prevailing technology?	Which proportion of the original NPP remains in ecosystems on a defined land area, given current land-cover patterns and land use practices?
Unit(s)	Global hectares; i.e., hectares of bioproductive land and sea area, with global average productivity	Joules, kilograms of dry-matter biomass or kilograms of carbon
Underlying assumption	Humans depend on the availability of bioproductive area; overuse depletes natural capital ("overshoot")	The percentage of NPP appropriated by humans is a useful measure of the "human domination" of ecosystems. High levels of HANPP are a potential risk to biodiversity
Relevance for sustainability	Comprehensive ecological accounts to compare the size of the human economy to the size of the supporting ecosystems. This allows one to detect ecological overshoot Can compare the "draw on nature" of different countries, regions, individuals, etc., thereby mapping ecological distribution conflicts	Assessment of land use on national territory. Identifies the intensity of use of a country's terrestrial ecosystems Current assessments do not identify a clear "sustainability threshold" Large reduction in productivity (low NPP_{act} compared to NPP_0) indicates inefficient land management

Emission itself may not require much area, but absorption of wastes does. For example, emitting CO_2 into the atmosphere does not need area per se, but area dedicated to absorbing carbon through afforestation could help to stabilize concentrations of atmospheric CO_2.

3. *Space occupied space for human infrastructure*: Humans occupy area not only for housing but also for work space, infrastructure (e.g., for transportation) as well as recreation, education, and many other culturally important human activities. Only a part of these area-demands can actually be quantified, however.

How well ecosystems perform these functions largely depends on their productivity. It is obvious that agriculture and forestry depend on the NPP of agro-ecosystems, which are the combined outcome of natural preconditions and present as well as past human management. But the 'waste absorption' function also may depend on primary production. For example, carbon absorption rates of forests depend on their productivity because net ecosystem productivity (i.e., the net carbon accumulation rate) is a fraction of NPP (see Fig. 1).[4] While the 'infrastructure space' function need not be dependent on ecosystem productivity, relatively few human settlements are situated in unproductive environments because humans predominantly live in areas where environmental conditions like climate and water availability favour human activities. These areas are typically highly productive, and productivity may often have influenced historical settlement patterns: only industrial, fossil-fuel-based societies can energetically afford to maintain large settlements in ecosystems with low productivity (e.g., through long-distance transport). Even today there are few large human settlements in deserts, arctic environments, high altitudes or other unproductive ecosystems.

EF and HANPP both consider all three-core functions of ecosystems for humans, but in different ways. EF assesses the area needed to sustain these three functions, to the exclusion of their use for other populations or activities. These areas can be outside of the given population's territory. HANPP assesses the changes in ecological energy flows in a defined land area, as depicted in Fig. 1, resulting from human use of these three ecosystem functions. In the following section we will discuss the underlying research questions and corresponding definitions of both EF and HANPP before comparing the two concepts in the discussion and conclusion.

Research questions and underlying assumptions

EF and HANPP are not simply 'given methodologies' but responses to specific research questions. The methodologies emerge from the nature of their distinct questions. This paper compares the research questions driving these two approaches, while the methodologies of both EF and HANPP are discussed in detail in other articles of this special issue (Monfreda et al., 2004; Wackernagel et al., 2004; Krausmann et al., 2004). Main points of the following discussion are summarized in Table 1 and Fig. 2.

EF: tracking overshoot

The driving question behind EF is: how big is a given population's draw on nature as compared with the

[4] This relation is non-linear, however. While young stands accumulate considerable amounts of carbon, most or even all NPP may be consumed by heterotrophs in old-growth forests so that they do not accumulate carbon.

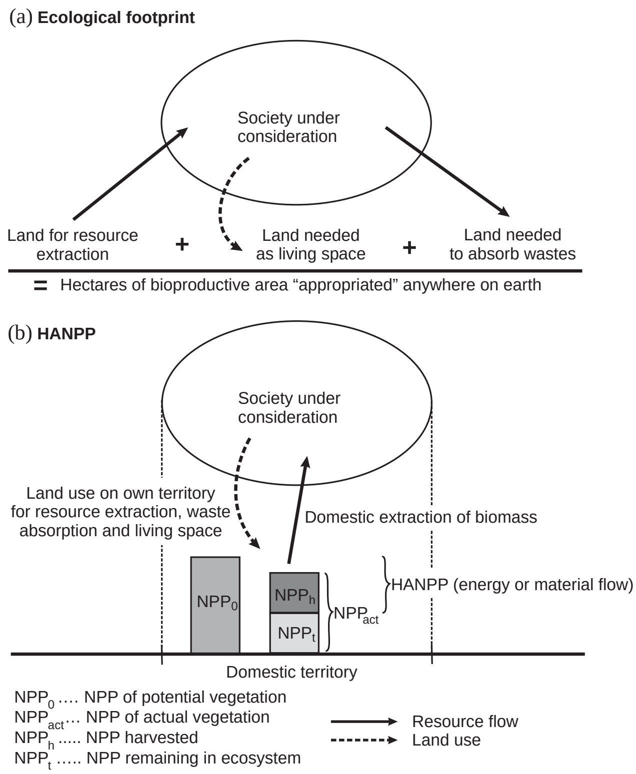

Fig. 2. Definition of the ecological footprint (EF) and human appropriation of net primary production (HANPP).

regenerative capacity of the biosphere? Or more precisely: how much biologically productive area of the biosphere, expressed in mutually exclusive hectares of land or sea area, is required in a given year—with the prevailing technology and resource management of that year—to renew that year's resource throughput of a defined human population? This 'population' can be an individual, a city, a region, or the world as a whole. The measure can even be extended to a product or an economic process. A corollary to the underlying research question is the distribution of this demand on the biosphere among given populations. EF assesses humanity's dependence on the biosphere's productivity in terms of the continuous flow of resources and other ecological services. This assessment builds on the assumption that human well-being will, at least in the long run, decline if human use of nature exceeds nature's regenerative capacity. Excess demand liquidates nature's capacity to provide a continuous volume of essential ecological services, undermining nature's ability to support the human economy (Wackernagel et al., 2002b).

As summarized in Fig. 2, EF of a population represents the biologically productive area necessary to provide humans with three core ecosystem functions: producing resources, hosting buildings and infrastructure, and absorbing wastes (Wackernagel and Rees, 1996). For people living in industrial societies, this area is typically scattered across many continents. EF is expressed in normalized or 'global hectares'. Each global hectare represents an equal portion of a given year's bioproductivity. The Earth's total number of global hectares equals its total number of biologically productive hectares. These global hectares are the standardized 'currency' of EF accounts. 'Usable bio-productivity' refers to the capacity to support the primary ecosystem function derived from a specific type of bioproductive area (Wackernagel et al., 1999). For example, timber is included; the ivy in the forest is not. EF calculations reflect the prevailing technology of the year to which the assessment refers. More efficient technology and more productive ecosystems reduce EF of a given consumption pattern.

Hence, EF calculates the bioproductive area needed to sustain a population's socio-economic metabolism (Haberl et al., 2001a) because it considers the total area needed to extract resources and absorb wastes, which include the area needed to transport, process and store all consumed products.

EF asks how much bioproductive area is needed exclusively for the activities of a given population, implying that this area is not available for serving other populations or activities. This area (demand) may then be compared to available bioproductive area (supply) which is called biocapacity. If humanity's footprint exceeds the global biocapacity, a state of 'overshoot' exists; that is, a situation where the draw on nature exceeds nature's regenerative capacity. Recent calculations suggest that humanity is currently in global overshoot in which global demand on nature exceeds the regeneration rate of the biosphere (Wackernagel et al., 2002b). Overshoot implies that natural capital is being liquidated, which not only makes less natural capital available in the future but may also compromise its ability to regenerate.

Average per-capita EF accounts of 146 nations have been constructed using internationally available statistics and data (Loh, 2002; Wackernagel et al., 2002a). EF also can be assessed for smaller population units: cities, households, or organizations (Sustainable Sonomy County and Redefining Progress, 2002). Being able to document the footprint of population groups or individuals allows researchers to compare the difference in the relative burden on the biosphere exerted by these various groups, thereby mapping ecological distribution conflicts (Martinez-Alier, 2002).

HANPP: Measuring human domination of ecosystems

In contrast to EF, which accounts for a population's demand for and supply of mutually exclusive areas, HANPP measures how intensively these areas are used (Haberl, 1997; Haberl et al., 2001b). Unlike EF, which refers to a defined socio-economic system or production process, HANPP refers to a defined land area. If applied on a national scale, HANPP evaluates the effects of people's activities[5] on the energetics of terrestrial ecosystems on a nation's territory (see Fig. 2).

The research questions behind HANPP are: how intensively is a defined area of land being used in terms of ecosystem energetics? On a given territory, how much energy is diverted by humans as compared with the energy potentially available? How strongly does human use of a defined land area affect its primary productivity, and how much of the NPP is harvested by humans and, therefore, not available for non-human processes? HANPP can be expressed as material flow (kg dry matter biomass), as a substance flow (kg carbon) or as an energy flow (Joule). Also, HANPP can be presented as a percentage of potential NPP. The analysis also reveals the components of HANPP; that is, potential NPP (NPP_0), actual NPP (NPP_{act}), NPP remaining in ecosystems (NPPt) and harvest.

The assumption behind HANPP is that the flow of trophic energy described in Fig. 1 is a prerequisite for the functioning of ecosystems, and that reducing energy availability for ecosystem processes such as the build-up and maintenance of biomass stocks or the flow of energy from autotrophs to herbivores, detritivores and carnivores of different trophic levels affects ecosystems (Lotka, 1925; Lindemann, 1942; Odum, 1971). For example, increases in HANPP may result in net carbon flows from ecosystems to the atmosphere, and there is an intensive, controversial debate on the potential effect of reduced energy availability on species diversity (e.g., Haberl et al., 2003b; Wright, 1990; Wright et al., 1993), although energy is only one of the factors that may influence biodiversity (Wrbka et al., 2004). On the other hand, HANPP is also useful to demonstrate the 'size' of the human component in an ecosystem (Daly, 1992).

However, the extent to which HANPP tracks the maintenance of the biosphere's capacity is less straightforward than in the case of EF, for at least two reasons:

1. There is no clear 'sustainability threshold'. While it is clear that 100% HANPP would be destructive because this would leave no resources for other species than those needed for human purposes, it is debatable how to set a meaningful lower threshold. Some have argued, based on the precautionary principle, that human impact should be 'small' compared to natural processes and have proposed a threshold of 20% HANPP (Weterings and Opschoor, 1992), but this number was not based on scientific criteria. Considering the present state of knowledge on ecological effects of HANPP (but see Wrbka et al., 2004), we are limited to vague statements such as "to the extent that (…) natural systems, species and populations provide goods or services that are essential to the sustainability of human systems, their shrunken base of operations must be a cause of concern" (Vitousek and Lubchenko, 1995, p. 60). Increases in HANPP may lead to carbon fluxes from biota to the atmosphere, they may contribute to biodiversity loss, and they may result in diminished resilience of ecosystems, but the effect of a given level (or time path) of HANPP remains unknown.
2. HANPP only refers to land use on a given territory. Demands of this territory's people on ecosystems outside the territory are ignored, and demands on the territory's ecosystem by people from outside the territory are not separated. The 'infrastructure space' function is considered in a similar way as in EF calculations. The 'waste absorption' function is currently only considered if waste treatment requires area, although land managed in order to serve absorptive functions would, in principle, be considered if this management entailed changes in the productivity of the affected area.

A main feature of HANPP is its spatially explicit analyses that can be linked to landscape-ecological studies or analyses of ecosystem functioning (Wrbka et al., 2004). Moreover, the contribution of different socio-economic sectors to the HANPP in a country can be evaluated. For example, biomass flow models that consider physical imports and exports (Haberl et al., 2003a) make it possible to calculate the contribution of different end uses to the HANPP in a country. Physical input–output tables (Duchin, 1998) would make it possible to link HANPP (and other indicators within the MEFA framework) to economic models (which is also possible for footprints; Hubacek and Giljum, 2003).

Important insights can be generated by looking at the components of HANPP. For example, if land management in a country results in a consistent downward trend of NPP_{act} this would be an early warning sign of environmental degradation (Munasinghe and Shearer, 1995). Moreover, the relation between various HANPP components—e.g., between harvest and HANPP or between NPP_{act} and NPP_0—sheds light on trends in land use over time (see Krausmann et al., 2004).

[5] On the national scale, HANPP evaluates the effects of all human activities taking place on national territory. These human actions are normally regulated by national laws, occur based on property rights according to the legal system of that country and are influenced by economic incentives depending on its national economy, but they need not be taken by citizens of this particular nation. HANPP calculations do not distinguish between land use for own consumption of a country and land use for export purposes (this aspect is taken care of in MFA or EFA).

Discussion and conclusions

Scope of analysis

The above discussion of research questions and underlying assumptions has shown that EF and HANPP start from different perspectives, examine different aspects of ecological impact, and consequently provide different insights (Fig. 2). EF assesses, as comprehensively as data availability allows, how much bioproductive area is needed exclusively to sustain the activities of a given society (i.e., EF calculations try to avoid double-counting of area). EF can be compared to the amount of bioproductive area available, and therefore facilitates the assessment of overshoot—an unsustainable situation characterized by overuse of the biosphere's regenerative capacity. Hence, EF addresses a necessary, but not sufficient, condition for natural-capital maintenance. It also highlights differences in demand on nature by various population groups. Both the former ecological and the latter social aspects are key to any sustainability analysis.

HANPP asks how intensively humans use a specific area, for example a national territory. HANPP can be used to evaluate to what extent humans dominate (or 'colonize'; Fischer-Kowalski and Weisz, 1999) the terrestrial ecosystems on a defined territory. HANPP calculations reveal how intensively and efficiently societies use their territories (Grünbühel et al., 2003; Haberl, 2001), how the use of ecosystems in a country changes over time (Krausmann, 2001) and what this means for carbon stocks (Haberl et al., 2001b), biodiversity (Haberl et al., 2003b) and landscape ecosystems (Wrbka et al., 2004). Although they may thus contribute to analysing sustainability problems, HANPP calculations do not provide a comprehensive judgement on whether a society is sustainable or not. For example, neither land use associated with imported biomass, nor any other fraction of a society's metabolism (e.g., fossil fuels, minerals, etc.) is considered in HANPP calculations.

Table 2 provides a comparison of EF and HANPP calculations to highlight the differences in the resources considered in the two approaches. It shows that there is overlap between the two concepts because both include domestic extraction of biomass and land used to host infrastructure. Nevertheless, considerable parts of socio-economic metabolism that are accounted for in EF are not part of HANPP calculations. Other tools of the MEFA framework, which includes HANPP, cover these resource aspects more comprehensively (Krausmann et al., 2004).

Units and spatial reference

EF is measured as 'global hectares' of bioproductive land. In order to convert physical hectares into global hectares (gha), the area of each category of land used is scaled up or down in proportion to its maximum potential crop yield using equivalence factors (Monfreda et al., 2004; Wackernagel et al., 1999; Wackernagel et al., 2002b). This can be done, for example, by using the global agro-ecological zones (GAEZ) published by the FAO and the IIASA (IIASA and FAO, 2000). These equivalence factors 'weigh' the utility of the land according to its potential for a specific human use: growing crops. As an example, equivalence factors and global average per capita demand are summarized in Table 3. The footprint equivalent to each unit of consumption of a resource is calculated by assuming the global average yield of this resource in a given year. For example, global average wheat yields as assessed by the FAO (http://apps.fao.org) are used for calculating EF resulting from the consumption of the wheat consumption of a country under consideration.

This assumption allows analysts to determine a given population's appropriation of the world's biocapacity. Nevertheless, for some purposes this approach may be

Table 2
Resource utilization of a nation considered in HANPP and EF calculations—a comparison

	EF	HANPP
Fossil fuel use	Various calculation approaches exist. One typically used, and leading to a lower area requirement than most other assessment methods, estimates area requirements for sequestering excess CO_2 emissions from fossil fuel burning	Area needed for domestic extraction
Minerals, metals	Area needed for extraction Energy embodied in processing of ores	Area needed for domestic extraction
Imported biomass	Considered, expressed in global hectares	Not considered. HANPP caused abroad by biomass imports could be calculated in principle, but this would be either rather imprecise or highly data-demanding
Domestically extracted biomass	Considered, expressed in global hectares	Considered as "harvest" (NPP_h) in HANPP calculation
Built-up area	Considered, assumes built-up area covers cropland with country's average productivity (due to lack of better data)	Reduces NPP_{act} as compared to NPP_0; i.e., HANPP of built-up area depends on its potential productivity

Table 3
Equivalence factors and global average per capita demand of bioproductive area

	Equivalence factor (gha/ha)	Total per capita area demand (ha/cap)	Equivalent total in global hectares (gha/cap)
Cropland	2.1	0.25	0.53
Grazing land	0.5	0.21	0.10
Forests	1.3	0.22	0.29
Fishing grounds	0.4	0.40	0.14
Built-up land	2.2	0.05	0.10
Fossil fuel and nuclear energy	1.3	0.86	1.16
Total			2.33

Source: Wackernagel et al. (2002b).

unsatisfactory since more efficient ecological production of one country (Ceteris paribus) will make the global hectares slightly more productive thereby slightly reducing all other countries' footprint. Some would argue it should show up as that country's reduced footprint only. This differentiation, however, is not a fundamental limitation of the EF method. Firstly, it merely reflects the underlying research question of analysing the draw on the global biocapacity. Second, when comparing the country's biocapacity to its ecological footprint, the country with higher agricultural efficiencies (Ceteris paribus) will show up with a more favourable ratio. This holds true even when looking at self-sufficient subsistence economies where consumption is essentially determined by local production and trade plays but a minor role (Grünbühel et al., 2003). For such an analysis, the unit of 'global hectare' may be unnecessarily artificial, and it may make more sense to use a standardized local hectare as the analytical unit when comparing the local consumption to the biocapacity of the region they depend on.

HANPP is measured in the same units normally used to assess primary productivity; that is, either as substance flow (kg carbon per year), as material flow (kg dry matter biomass per year) or as energy flow (Joules per year). Results derived in these different units are similar but not identical, because the carbon content of biomass can vary between 42–55% (Schulze, 2000) and energy density (calorific value) of dry matter biomass ranges from about 15–30 MJ/kg, although most quantitatively relevant biological materials fall into a range of 17–21 MJ/kg (Golley, 1961). HANPP may in principle be calculated for any square metre of the area under consideration. In practice the land is normally broken down into units (grid cells, polygons, sums of the area of defined land-cover classes, etc.) assumed to be uniform with respect to potential NPP, actual NPP and harvest. That means two things: (1) If the units are defined in a spatially explicit way (e.g., as grid cells or polygons in a GIS), it is possible to use the results for mapping. In this case, the result is much more than one average value for a country because it can be used to analyse spatial patterns in human use of ecosystems (Wrbka et al., 2004). (2) If the results are aggregated—e.g., in a national or global total—areas are implicitly 'weighted' according to their potential or actual primary productivity, not according to their usefulness for human purposes.

Both aggregation approaches have their advantages: aggregating areas according to their maximum potential crop yield provides a simple, yet meaningful way to evaluate the value of different kinds of land for human sustenance. This follows from the anthropocentric perspective inherent in EF calculations and provides a way to calculate aggregate overshoot as well as overshoot in various natural capital categories (for example, depletion of biomass stocks in forests, overharvest of fish stocks in oceans, or accumulation of anthropogenic CO_2 in the atmosphere).

If different land units are aggregated in HANPP calculations, this is done according to actual or potential biophysical characteristics (i.e., primary productivity) of the land, not according to its potential or actual socioeconomic value. Actual NPP of the land is, of course, the combined outcome of biophysical potential and human management, and it may *determine* the utility of land for humans. The difference between NPP_0 and NPP_{act} is a measure for the efficiency with which land is used: If NPP_{act} is much lower than NPP_0 then one can assume that a considerable amount of the production potential of the land remains unused, resulting in the necessity to use more land to produce the same amount of biomass for human purposes (Grünbühel et al., 2003; Krausmann, 2001; Krausmann and Haberl, 2002). But the calculation method itself is not dependent on human preferences, economic institutions, technology, etc.[6] An advantage of this is that, as long as enough data are available, HANPP can be calculated in a way that makes comparison possible for any kind of human society, from hunter gatherers to industrial societies (Haberl, 2001).

Usefulness for communication and policy advice

EF is an effective tool to communicate the reality and potential implications of ecological overshoot, a core

[6] Of course, defining HANPP in a specific way implies the value judgement that the figure calculated according to this definition is useful. By contrast, aggregating land according to an index judging its current production potential for crops implies that crop production is the socially most important function of land, at least for the kind of aggregation under consideration. Other social perspectives might lead to other kinds of valuation, while the biophysical process of primary production measured in physical units is independent of social valuation.

driver behind the unsustainable state of the world (e.g., Wackernagel et al., 2002b). It also demonstrates how much the consumption patterns of different populations contribute to this state of affairs.[7] Although HANPP has received some attention among natural scientists (Rojstaczer et al., 2001; Vitousek et al., 1997) and ecological economists (Costanza et al., 1998; Martinez-Alier, 1998), the broader audience has not picked it up widely. Two factors may contribute to this communication deficit: (1) HANPP is an abstract concept about aggregate energy or material flows, measured in units that are hard to relate to everyday experiences, whereas EF is measured in hectares, a unit everyone can understand. (2) EF calculations arrive at clear-cut conclusions about violations of ecological limits whereas the consequences of a region's HANPP value of, for example, 20%, 50% or 80% remains unclear, at least at present. More research on the ecological effects of HANPP such as that presented in this special issue (Wrbka et al., 2004) is needed.

Both EF and HANPP have been used to bring ecological constraints and their potential implications for human well-being to the attention of a wider audience. Judging from its wide presence on the internet in academic discussions and among NGO campaigns, EF has so far been more successful than HANPP in this respect. EF's ability to communicate well is a major factor behind this success.

Both concepts, however, are still too crude to provide specific and comprehensive policy guidance. One reason is that EF still leaves out significant components of ecological demand on nature. For instance, since acid rain is not included in present accounts, the accounts are insensitive to changes in the emissions of acidifying substances. Also, EF reductions achieved through more intensive (and possibly more destructive) uses of nature, as potentially in the case of more industrial agriculture,[8] may in reality defeat the intended purpose of reducing human demand on nature. Such destructive uses would only show up as reduced biocapacity in future years, but are not predicted by EF accounts. Nevertheless, EF is able to frame the challenge and communicate possible choices for living within the 'budget of nature'. For policy implementation, EF needs to be complemented with harder targets (such as CO_2 emission targets, water consumption targets or nature conservation targets) in order to make policy demands more specific and evaluation effective.

The utility of HANPP for policy-advice is currently hampered by poor understanding of HANPP's ecological effects that does not allow to define meaningful 'sustainability thresholds'. HANPP could, however, play an important role as an indicator for human pressures on biodiversity if clear causal and empirical relations between HANPP and biodiversity were established. Current work (Haberl et al., 2003b; Wrbka et al., 2004) suggests that there probably exist non-linear relations between energy remaining in ecosystems and biodiversity, although, as indicated above, energy is probably only one among many factors behind biodiversity patterns.

Concluding remarks

We conclude that EF and HANPP ask questions about different facets of ecological impact. EF measures exclusivity of use, while HANPP measures intensity of use, making them complementary metrics. EF is an efficient tool to evaluate overshoot and communicate the results to a broad audience. It calculates the amount of bioproductive area needed exclusively to sustain the activities of a defined human population, and it provides an aggregate figure of the human draw on nature. It also serves to document ecological distribution conflicts. HANPP assesses the extent of 'human domination', or the 'intensity of socio-economic colonization' of a given terrestrial ecosystem or region, but it includes a more limited subset of resources than EF.

EF and HANPP focus on different aspects of a society's draw on ecosystems. While EF includes trade to appraise a society's appropriation of biocapacity domestically and abroad, HANPP has thus far concentrated on domestic impacts. Aggregate HANPP related to a society's imports and exports could, in principle, be assessed, but such appraisals would be quite demanding and could still only be based on country-averages for different traded products. This would introduce inaccuracies.

EF differentiates between domestic extraction and import (Haberl et al., 2001a; Monfreda et al., 2004), but insufficient data exist to link each consumption item to its spatially explicit origin (but see Erb, 2004). The biocapacity component of EF accounts can, however, be spatially mapped. HANPP can be used for spatially explicit analyses and is therefore able to relate a society's metabolism to land use and its effects on ecosystem functioning. It is thus a promising approach for linking analytical tools such as material flow analysis (MFA) or approaches such as industrial ecology to landscape ecology or biogeophysical analyses of environmental change.

[7] These accounts also track the demand on nature from their production patterns. This is the amount of ecological capacity necessary to maintain the economic activities associated with their income generation.

[8] Increasing yields typically requires fossil energy. Although this fossil energy is included in EF, examples such as an EF time series for Austria 1926–1995 (Haberl et al., 2001a) suggest that the additional fossil-fuel footprint is small compared to the reduction in area demand gained through agricultural intensification.

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References

Ajtay, G.L., Ketner, P., Duvigneaud, P., 1979. Terrrestrial primary production and phytomass. In: Bolin, B., Degens, E.T., Kempe, S., Ketner, P. (Eds.), The Global Carbon Cycle. Wiley, Chichester, New York, Brisbane, Toronto, pp. 129–182.

Boyden, S., 1992. Biohistory, The interplay between human society and the biosphere. UNESCO and Parthenon Publishing Group, Paris, Casterton Hall, Park Ridge.

Butzer, K.W., 1984. Archaeology as Human Ecology. Cambridge University Press, Cambridge, MA.

Costanza, R., Farber, S., 2002. The dynamics and value of ecosystem services: integrating economic and ecological perspectives. Special Issue of Ecological Economics 41 (3), 367–560.

Costanza, R., Cumberland, J., Daly, H.E., Goodland, R., Norgaard, R., 1998. In: An Introduction to Ecological Economics. CRC Press, Boca Raton, FL/USA.

Daily, G.C., 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, Washington, DC.

Daly, H.E., 1992. Vom Wirtschaften in einer leeren Welt zum Wirtschaften in einer vollen Welt. In: Goodland, R., Daly, H.E., Serafy, S.E., Droste, B. (Eds.), Nach dem Brundtlandbericht: Nachhaltige Wirtschaftliche Entwicklung. Deutsche UNECSO-Kommission, Bonn, pp. 29–40.

Duchin, F., 1998. Structural economics. Measuring Change in Technology, Lifestyles, and the Environment. The United Nations University, Island Press, Washington, DC, Covelo, CA.

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.

Erb, K.-H., 2004. Actual land demand of Austria 1926–2000: A variation on ecological footprint assessments. Land Use Policy, doi:10.1016/j.landusepol.2003.10.010.

Fischer-Kowalski, M., Haberl, H., 1997. Tons, joules and money: modes of production and their sustainability problems. Society and Natural Resources 10 (1), 61–85.

Fischer-Kowalski, M., Weisz, H., 1999. Society as hybrid between material and symbolic realms, toward a theoretical framework of society–nature interrelation. Advances in Human Ecology 8, 215–251.

Golley, F.B., 1961. Energy values of ecological materials. Ecology 42 (3), 581–584.

Grünbühel, C.M., Haberl, H., Schandl, H., Winiwarter, V., 2003. Socio-economic metabolism and colonization of natural processes in SangSaeng village: material and energy flows, land use, and cultural change in northeast Thailand. Human Ecology 31(1) 53-86.

Haberl, H., 1997. Human appropriation of net primary production as an environmental indicator: implications for sustainable development. Ambio 26 (3), 143–146.

Haberl, H., 2001. The energetic metabolism of societies, Part II: empirical examples. Journal of Industrial Ecology 5 (2), 71–88.

Haberl, H., Schandl, H., 1999. Indicators of sustainable land use: concepts for the analysis of society–nature interrelations and implications for sustainable development. Environmental Management and Health 11 (3), 177–190.

Haberl, H., Erb, K.H., Krausmann, F., 2001a. How to calculate and interpret ecological footprints for long periods of time: the case of Austria 1926–1995. Ecological Economics 38 (1), 25–45.

Haberl, H., Erb, K.H., Krausmann, F., Loibl, W., Schulz, N., Weisz, H., 2001b. Changes in ecosystem processes induced by land use: human appropriation of net primary production and its influence on standing crop in Austria. Global Biogeochemical Cycles 15 (4), 929–942.

Haberl, H., Erb, K.-H., Krausmann, F., Adensam, H., Schulz, N., 2003a. Land-use change and socioeconomic metabolism in Austria, Part II: land-use scenarios for 2020. Land Use Policy 20 (1), 21–39.

Haberl, H., Schulz, N., Plutzar, C., Erb, K.H., Krausmann, F., Loibl, W., Moser, D., Sauberer, N., Weisz, H., Zechmeister, H.G., Zulka, P., 2003b. Human appropriation of net primary production and species diversity in agricultural landscapes. Agriculture, Ecosystems and Environment, in print.

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H., Winiwarter, V., 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy, submitted.

Hubacek, K., Giljum, S., 2003. Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. Ecological Economics 44, 137–151.

IIASA and FAO, 2000. Global agro-ecological zones 2000. Rome, Italy, International Institute for Applied Systems Analysis (IIASA) and food and agriculture organization (FAO).

Krausmann, F., 2001. Land use and industrial modernization, an empirical analysis of human influence on the functioning of ecosystems in Austria 1830–1995. Land Use Policy 18 (1), 17–26.

Krausmann, F., Haberl, H., 2002. The process of industrialization from the perspective of energetic metabolism, socioeconomic energy flows in Austria 1830–1995. Ecological Economics 41 (2), 177–201.

Krausmann, F., Haberl, H., Erb, K.-H., Wackernagel, M., 2004. Resource flows and land use in Austria 1950–2000: using the MEFA framework to monitor society–nature interaction for sustainability. Land Use Policy, doi:10.1016/j.landusepol.2003.10.005.

Lindemann, R.L., 1942. The trophic-dynamic aspect of ecology. Ecology 23 (4), 399–418.

Loh, J., 2002. In: Living Planet Report 2002. World Wide Fund for Nature (WWF) International, Gland, Switzerland.

Lotka, A.J., 1925. Elements of Physical Biology. Williams & Wilkins Company, Baltimore.

Martinez-Alier, J., 1998. Ecological Economics as Human Ecology. Fundación César Manrique, Madrid.

Martinez-Alier, J., 2002. The Environmentalism of the Poor, A Study of Ecological Conflicts and Valuation. Edward Elgar, Cheltenham, UK, Northampton, MA, USA.

Monfreda, C., Wackernagel, M., Deumling, D., 2004. Establishing national natural capital accounts based on detailed ecological footprint and biological capacity accounts. Land Use Policy, doi:10.1016/j.landusepol.2003.10.009.

Munasinghe, M., Shearer, W., 1995. An Introduction to the Definition and Measurement of Biogeophysical Sustainability. In: Munashinghe, M., Shearer, W. (Eds.), Defining and Measuring Sustainability, The Biogeophysical Foundations. United Nations University and The World Bank, Washington, DC, pp. xvii–xxxiii.

Munro, D.A., 1991. Caring for the Earth, A Strategy for Sustainable Living. IUCN, UNEP, WWF, Gland.

Odum, E.P., 1971. Fundamentals of Ecology. W.B. Saunders, Philadelphia, PA.

Rojstaczer, S., Sterling, S.M., Moore, N., 2001. Human appropriation of photosynthesis products. Science 294, 2549–2552.

Schlesinger, W.H., 1997. Biogeochemistry, An Analysis of Global Change. Academic Press, San Diego.

Schulze, E.D. (Ed.), Carbon and Nitrogen Cycling in European Forest Ecosystems. Ecological Studies., Vol. 142. Springer, Berlin, Heidelberg, New York.

Sieferle, R.P., 1997. Rückblick auf die Natur, Eine Geschichte des Menschen und seiner Umwelt. Luchterhand Verlag, München.

Smil, V., 1992. General Energetics, Energy in the Biosphere and Civilization. Wiley, New York.

Stöglehner, G., 2003. Ecological footprint—a tool for assessing sustainable energy supplies. Journal of Cleaner Production 11, 267–277.

Sustainable Sonomy County and Redefining Progress, 2002. Time to Lighten Up? Report on the Sonoma County Ecological Footprint Project. Sustainable Sonomy County, Sebastopol, CA.

Vitousek, P.M., Lubchenko, J., 1995. Limits to sustainable use of resources: from local effects to global change. In: Munashinghe, M., Shearer, W. (Eds.), Defining and Measuring Sustainability, The Biogeophysical Foundations. United Nations University and The World Bank, Washington, DC, pp. 57–64.

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

Wackernagel, M., Rees, W., 1996. Our Ecological Footprint, Reducing Human Impact on the Earth. New Society Publishers, Gabriola Island, Philadelphia.

Wackernagel, M., Lewan, L., Borgström-Hansson, C., 1999. Evaluating the use of natural capital with the ecological footprint, applications in Sweden and subregions. Ambio 28 (7), 604–612.

Wackernagel, M., Monfreda, C., Deumling, D., 2002a. The Ecological Footprints of Nations: How Much Nature Do They Use? How Much Nature Do They Have. Sustainability Issue Brief, Redefining Progress, Oakland, CA.

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002b. Tracking the ecological overshoot of the human economy. Proceedings of the National Academy of Sciences 99 (14), 9266–9271.

Wackernagel, M., Monfreda, C., Schulz, N.B., Erb, K.-H., Haberl, H., Krausmann, F., 2004. Calculating national and global ecological footprint time series: Resolving conceptual challenges. Land Use Policy, doi:10.1016/j.landusepol.2003.10.006.

Weterings, R.A.P.M., Opschoor, J.B., 1992. The Ecocapacity as a Challenge to Technological Development. Advisory Council for Research on Nature and Environment, Rijswijk.

Wrbka, T., Erb, K.-H., Schulz, N.B., Peterseil, J., Hahn, C.O., Haberl, H., 2004. Linking pattern and process in cultural landscapes. An empirical study based on spatially explicit indicators. Land Use Policy, submitted.

Wright, D.H., 1990. Human impacts on the energy flow through natural ecosystems, and implications for species endangerment. Ambio 19 (4), 189–194.

Wright, D.H., Currie, D.J., Maurer, B.A., 1993. Energy supply and patterns of species richness on local and regional scales. In: Ricklefs, R.E., Schluter, D. (Eds.), Species Diversity in Ecological Communities. The University of Chicago Press, Chicago, London, pp. 66–76.