Ecological Economics 69 (2009) 250–259

Contents lists available at ScienceDirect

Ecological Economics

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

Analyzing the global human appropriation of net primary production — processes, trajectories, implications. An introduction☆

Karl-Heinz Erb [a,*], Fridolin Krausmann [a], Veronika Gaube [a], Simone Gingrich [a], Alberte Bondeau [b], Marina Fischer-Kowalski [a], Helmut Haberl [a]

[a] Institute of Social Ecology, Alpen-Adria University Klagenfurt – Graz – Wien, Schottenfeldgasse 29, 1070 Vienna, Austria
[b] Potsdam Institute of Climate Impact Research, P.O. Box 60 12 03, 14412 Potsdam, Germany

ARTICLE INFO

Article history:
Received 6 March 2009
Received in revised form 30 June 2009
Accepted 1 July 2009
Available online 5 August 2009

Keywords:
Human appropriation of net primary production
Biophysical indicators
Land use
Biomass flows
Socioeconomic drivers
Strong sustainability

ABSTRACT

Humanity's role in shaping patterns and processes in the terrestrial biosphere is large and growing. Most of the earth's fertile land is used more or less intensively by humans for resource extraction, production, transport, consumption and waste deposition or as living space. Biomass production on cropland, grazing areas and in managed forests dominates area requirements, but other processes such as soil degradation, human-induced fires and expansion of settlements and infrastructure play an increasingly important role as well. The growing human domination of terrestrial ecosystems contributes to biodiversity loss as well as to a reduced capability of ecosystems to deliver vital services such as buffering capacity, soil conservation or self-regulation. This special section is devoted to the presentation of recent research into the patterns, determinants and implications of the human appropriation of net primary production (HANPP), an integrated socio-ecological indicator of land use intensity. By measuring the combined effect of land conversion and biomass harvest on the availability of trophic energy (biomass) in ecosystems, HANPP explicitly links natural with socioeconomic processes and allows for integrated analyses of land systems. This introductory article explains the rationale that links current HANPP research to Ecological Economics and discusses issues of definition and methods shared by all articles included in the special section. Finally, it gives an overview of the individual papers, provides some general conclusions and presents an outlook for future research: a better understanding of long-term trajectories of HANPP, of the significance of trade patterns as well as of the future role of bioenergy are highlighted as important issues to be addressed in the coming years.

1. Introduction

Humanity's impact on patterns and processes in the biosphere, such as biophysical properties (e.g. albedo, surface roughness, and surface temperature), plant cover, primary production, biodiversity, and biogeochemical cycles has become paramount (Vitousek et al., 1997; Millennium Ecosystem Assessment, 2005; Steffen et al., 2007). In some places, and for selected processes even on the global scale, socioeconomic drivers are beginning to overwhelm the great forces of nature, thereby inspiring researchers to introduce a new geological era, the 'anthropocene' (Crutzen and Steffen, 2003; Steffen et al., 2007), and to explicitly include human–nature interactions in ecological studies (Ellis and Ramankutty, 2008). Up to 83% of the global terrestrial biosphere except Greenland and Antarctica is considered to be under direct human influence (Sanderson et al., 2002). About 36% of the Earth's bioproductive surface has been classified as "entirely dominated by man" (Hannah et al., 1994). Changes in the terrestrial ecosystems resulting from land use are acting as pervasive drivers of global environmental change (Turner et al., 1990). It is increasingly acknowledged that land use results in sustainability challenges that are equally important and pressing as the potential threats resulting from global atmospheric and climatic change (Andreae et al., 2004; Haberl et al., 2004b; Foley et al., 2005). There is a growing recognition that integrated socio-ecological approaches are required to adequately grasp these sustainability challenges arising from global land system change (GLP, 2005; Turner et al., 2007).

Land is used by human societies for at least three core functions or services (Dunlap and Catton, 2002; Millennium Ecosystem Assessment, 2005): (1) Supply of vital material and energy resources such as fossil fuels, minerals, water, biomass and others. One important distinction that is useful here is that between "renewable" resources taken from current biogeochemical cycles (biomass, water, hydro or wind power, etc.) and "non-renewable" resources taken from geological deposits (fossil fuels, minerals, etc.). The provision of both kinds of resources requires land, but the area required per unit of mass or energy tends to

☆ Special issue: "Analyzing the global human appropriation of net primary production: Trajectories, processes and implications", Guest eds. Karl-Heinz Erb, Helmut Haberl, Fridolin Krausmann.

* Corresponding author. Tel.: +43 1 5224000 405; fax: +43 1 5224000 477.
E-mail address: karlheinz.erb@uni-klu.ac.at (K.-H. Erb).
URL: http//www.uni-klu.ac.at/sosec.

0921-8009/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2009.07.001

be much larger (by factors that are typically between 1:10^2 and 1:10^4) for biomass than for all other resources (Haberl and Schandl, 1999). (2) Waste absorption, buffering and regulating capacity of ecosystems. (3) Space required for hosting human infrastructures such as settlements, production sites, gardening and recreation areas and transport infrastructure. The provision of many ecosystem services, in particular the functions (1) and (2) above, often directly depend on the biological productivity of the land; that is, on its net primary production or NPP (Daily et al., 1997; Millennium Ecosystem Assessment, 2005; Krausmann et al., 2009). NPP is defined as the amount of biomass produced by green plants through photosynthesis per unit of time (usually one year) and space and is a decisive factor for a broad range of patterns and processes in ecosystems, including biodiversity, stocks and flows of carbon and other elements, food webs and water flows, as well as ecosystem resilience (Holling, 1973).

Land use results in changes in biomass flows in ecosystems that can be monitored using an indicator denoted as the human appropriation of net primary production (HANPP). Two interlinked processes are reflected by HANPP: (1) Land use changes that modify the NPP of the vegetation compared to the (potential) undisturbed vegetation. This first component of HANPP is denoted as ΔNPP_{LC} (change in NPP resulting from land conversion). ΔNPP_{LC} is defined as the difference between the NPP of potential vegetation (Tüxen, 1956), denoted as NPP_0, and the NPP of the currently prevailing vegetation, denoted as NPP_{act}. (2) The extraction or destruction of a fraction of the NPP for human purposes, e.g. through biomass harvest or grazing of livestock. This flow is denoted as NPP_h. HANPP is defined as the sum of ΔNPP_{LC} and NPP_h, and is an indicator for human-induced changes in the yearly availability of trophic energy in the ecosystems (Haberl, 1997; Haberl et al., 2007). Thus HANPP is an indicator of land use intensity that explicitly links natural with socioeconomic processes, generating an integrated picture of socio-ecological conditions in the land system (Krausmann et al., 2009), a notion that expresses the integrated, multifaceted interplay of terrestrial ecosystems and social systems (GLP, 2005). This special issue is devoted to the discussion of recent research into the patterns, determinants and implications of global HANPP.

HANPP is directly related to important global sustainability issues such as the endemic malnourishment of a large proportion of the world population (FAO, 2005), the ongoing conversion of valuable ecosystems (e.g., forests) to infrastructure, cropland or grazing land (FAO, 2004; Millennium Ecosystem Assessment, 2005; Lambin and Geist, 2006), with detrimental consequences for biodiversity (Heywood and Watson, 1995) and global, human-induced alterations of biogeochemical cycles (Crutzen and Steffen, 2003; Steffen et al., 2004). HANPP is relevant in the context of global water flows (Gerten et al., 2005), carbon flows (DeFries et al., 1999; McGuire et al., 2001) and — as biomass contains nitrogen (N), and N fertilizer is an important factor for agricultural productivity — N flows. As changes in the processes underlying these flows are essential for the ability of the ecosystems to provide goods and services to society in the long run, HANPP is also important in socioeconomic terms.

NPP is a central parameter of ecosystem functioning (Lindeman, 1942; Whittaker and Likens, 1973) that determines the amount of trophic energy available for transfer from plants to other levels in the trophic webs in ecosystems. Many aspects of ecosystem functioning such as nutrient cycling, build-up of organic material in soils or in the aboveground compartment of ecosystems, vitally depend on this energy flow. Thus, NPP is closely related to the resilience of ecosystems and to their capacity to provide services to humans, such as supplying biomass through agriculture and forestry, but also the buffering capacity or the absorption capacity for wastes and emissions (Daily et al., 1997; Millennium Ecosystem Assessment, 2005). Human alterations of the availability of NPP in ecosystems are therefore ecologically relevant almost by definition (Wright, 1983; Vitousek et al., 1986; Wright, 1990; Kay et al., 1999; Gaston, 2000). Moroever, recent research suggests that HANPP may be a potent indicator of human pressures on biodiversity, as empricial research in Austria suggested(Haberl et al., 2004a; Haberl et al., 2005). Nevertheless, despite a broad acknowledgement of a strong interrelation between NPP and biodiversity, the mathematical form of this interrelation remains disputed (Waide et al., 1999; Haberl et al., 2009), which renders more empirical research highly desirable.

As the earth's biologically productive land surface is limited, bioproductive land has often been proposed to be one major factor that might constrain the growth of human population numbers (Cohen, 1995) or the world economy (Meadows et al., 1972). Studies of global HANPP have gained attention in the literature on sustainable development because HANPP was often interpreted as an indicator for ecological limits to growth (Meadows et al., 1992; Sagoff, 1995; Costanza et al., 1998). This notion has meanwhile lost credit because (a) economic growth may proceed even without growing biomass use and (b) long-term studies of HANPP have shown that HANPP may decline even if biomass harvest grows due to agricultural intensification (Davidson, 2000; Haberl et al., 2001; Krausmann, 2001; Krausmann et al., 2009).

Emphasizing a multitude of socioeconomic and ecological aspects of HANPP, this special issue aims to elucidate the complex interaction between factors and processes such as production and consumption, technology, population density, land use policy, agrarian systems, human-induced fires, soil degradation, energy and many more in determining patterns and trajectories of global HANPP. This introductory article proceeds as follows: the next section discusses issues of definition underlying all contributions assembled in this special issue. Then we go on to describe fundamental aspects of methods and data used to assess HANPP in the papers in this special issue. Finally, we give a short overview of the individual articles and then present conclusions and an outlook to future HANPP research.

2. Defining the human appropriation of net primary production

Concerns about the human use of NPP were first voiced in the early 1970s, when prominent ecologists performed first rough calculations on the amount of biomass consumed by humans (Whittaker and Likens, 1973). Their assessment included only the harvest of food and wood for direct human consumption and suggested that humans were just using a few percent of the biosphere's yearly global NPP, an amount that hardly caused concerns. This changed with the prominent study by Vitousek et al. (1986) that painted a completely different picture, mainly because these authors also presented calculations of HANPP based on a much more inclusive definition. This study led to the famous result that humans actually used, co-opted or diverted almost 40% of the terrestrial NPP in the early 1980s. Since that time, a number of global HANPP results have been published (Wright, 1990; Rojstaczer et al., 2001; Imhoff et al., 2004; Haberl et al., 2007). These studies produced widely diverging results and suggested that HANPP might be as low as 3% or even as high as 55% (Table 1) — thus nurturing the suspicion that HANPP was difficult to measure and highly uncertain (Rojstaczer et al., 2001; Haberl et al., 2002). However, differences in definitions underlying the various studies were much more important for producing a wide variety of results than data uncertainties (which exist as well, of course).[1] This finding is corroborated by the fact that a recalculation of HANPP according to the definitions by Vitousek et al. (1986) based on the dataset of Haberl et al. (2007) yielded similar results, in particular for the intermediate and high estimates and for HANPP expressed as percent of NPP_0 (Table 1).

[1] The study by Rojstaczer et al. (2001) that found an exceedingly large error margin (10–55%) was based on the "intermediate" definition by Vitousek and others. However, this study failed to use the full extent of the available data, thereby arriving at a seriously exaggerated estimate of the uncertainty of HANPP calculations (see Field, 2001; Haberl et al., 2002; Haberl et al., 2007).

Table 1
Estimates of global HANPP published by various authors using different definitions of HANPP.

Reference	Definition (see text for details)	Terrestrial HANPP absolute [10^9 t dry matter/yr]	Terrestrial HANPP relative [%]
Whittaker and Likens, 1973	Human food and wood harvest	3.2	3.0%
Vitousek et al., 1986	"Low": food, fodder and wood	5.2	3.5%
	"Intermediate": low plus NPP of human-dominated areas	40.6	27.1%
	"High": intermediate plus ΔNPP_{LC}	58.1	38.8%
Wright, 1990	ΔNPP_{LC} plus some biomass harvest, excludes harvest in forests	35.0	23.1%
Rojstaczer et al., 2001	Vitousek et al. intermediate	39 (12–66)	32% (10–55%)
Imhoff et al., 2004	Biomass consumption multiplied by factors reflecting "upstream" flows (excl. ΔNPP_{LC})	23.1 (16.0–29.6)	20.3% (14.1–26.1%)
Recalculation of the Vitousek et al., 1986 definitions by Haberl et al., 2007	"Low"	10.3	7.8%
	"Intermediate"	35.9	27.4%
	"High"	48.5	37.0%
Haberl et al., 2007	Definition explained in this article	31.2	23.8%

Original data were converted to tons of dry matter biomass assuming 50% carbon content and a gross calorific value of biomass of 18.5 MJ/kg. Relative HANPP data are expressed as percent of NPP_0 except for the studies by Rojstaczer et al. and Imhoff et al. that do not include an NPP_0 value — in the latter cases the percentages reported here refer to NPP_{act}. More detailed discussions of the definitions are included in the text.

Whittaker and Likens (1973) included in their definition only food consumed by humans and wood harvested for human consumption. The "low" definition proposed by Vitousek et al. (1986) takes a similar approach, but also includes the fodder consumed by livestock. Their result is higher than that by Whittaker and Likens because of the increase in consumption between the early 1970s and the 1980s and because of the inclusion of fodder. Vitousek et al.'s "intermediate" definition adds to their "low" definition the total NPP of human-dominated ecosystems (e.g., croplands and forest plantations). Their most inclusive "high" definition additionally considers the NPP lost due to human-induced changes in the ecosystem productivity, e.g. ecosystem degradation (in our terminology: ΔNPP_{LC}).

Vitousek's first and second definition could lead to problematic results, however. As demonstrated for Austria, changes in agricultural technology have raised aboveground productivity on agricultural land by a factor of 2.6 from 1830 to 1995 (Krausmann, 2001). Consider, for example, one average hectare of cropland in Austria: According to Vitousek's intermediate definition, one would find an increase in HANPP by a factor of about 2.6 due to the increase in harvest, although the NPP remaining in the ecosystem (NPP_t) stayed near zero, because the increase in the agro-ecosystem's productivity (NPP_{act}) was compensated for by a similar increase in the harvest (NPP_h). Regarding all NPP of human-dominated ecosystems as appropriated, as Vitousek et al.'s third definition does, is also problematic: in forest plantations and grasslands a considerable fraction of the NPP remains in the ecosystem and supports food chains not directly controlled by humans. This argument has already been used to assume that the HANPP approach would result in inflated numbers of human impacts on the biosphere and to thereby question the HANPP concept altogether (Davidson, 2000).

Wright (1990), who was primarily concerned with human impacts on biodiversity, proposed to define HANPP as the difference in NPP available in (hypothetical) undisturbed ecosystems and the amount of NPP actually available to support heterotrophic food chains — in principle the same approach as the one used here. This definition succeeded in overcoming some of the problems associated with the approach of Vitousek et al. However, Wright excluded activities such as logging and biomass burning in forests on the grounds that harvest in forests, while removing energy, would not result in a long-term reduction of productivity of the land for wild species if forests were allowed to regrow. Although this argument may be correct as long as nutrient-rich parts (e.g., leaves) remain in the forest, it does not justify the exclusion of wood harvests from the definition of HANPP, first, because it represents an important socioeconomic biomass flow, and second, because there is ample evidence that biomass withdrawals from forest ecosystems result in significant ecological pressures (Harmon et al., 1986, 1990; Wardle et al., 2004). The associated NPP_h should therefore be included in any definition of HANPP.

Imhoff et al. (2004) calculated the global human consumption of NPP — which is a considerably different approach from those taken in all other papers included in Table 1 — but nevertheless denoted the resulting figures also as "HANPP." The definition used by Imhoff et al. was between the first two definitions of Vitousek: it did not include the total NPP of human-dominated ecosystems, but parts of plants not actually harvested, such as roots were considered if they were required for producing the harvested material. Neither Rojstaczer et al. (2001) nor Imhoff et al. (2004) considered changes in NPP caused by past or present land use (ΔNPP_{LC}).

In our work, as well as all papers assembled in this special issue, we defined HANPP as summarized in Fig. 1. This is related to Wright's (1990) suggestion and defines HANPP as the difference between the amount of NPP that would be available in an ecosystem in the absence of human activities (NPP_0) and the amount of NPP that actually remains in the ecosystem, or in the ecosystem that replaced it under current management practices (NPP_t). NPP_t can be calculated by quantifying the NPP of the actual vegetation (NPP_{act}) and subtracting

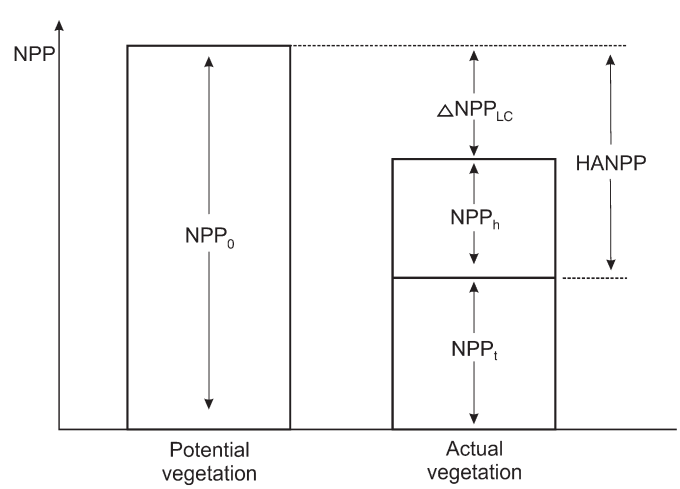

Fig. 1. Definition of HANPP used in the set of papers assembled in this special issue. From a societal perspective, HANPP measures the combined effect of land use induced changes in NPP (ΔNPP_{LC}) and biomass harvest (NPP_h). From an ecological perspective, HANPP is defined as the difference in the amount of NPP that would be available in the absence of human intervention (NPP_0) and the fraction of NPP remaining in ecosystems after human harvest under current conditions (NPP_t). Note that NPP_{act} may be larger than NPP_0 due to intensive land management, such as fertilization or irrigation; thus, ΔNPP_{LC} or even HANPP can be negative. Sources: Redrawn after Haberl (1997), Haberl et al. (2001), Krausmann et al. (2009).

from that the amount of NPP harvested by humans (NPP_h). If defined in that way, HANPP is a measure of human impacts on the yearly availability of trophic energy in terrestrial ecosystems. Increases in HANPP indicate an increased human domination of ecological energy flows through land use and thus of the intensity of direct human intervention into the terrestrial ecosystems.

HANPP, according to our definition, can be interpreted from a societal perspective as well as from an ecological perspective. From a societal perspective, HANPP is the aggregate effect of changes in productivity resulting from land conversion and use (ΔNPP_{LC}) and biomass harvest (NPP_h). From an ecological perspective, HANPP measures the human impact on the availability of energy in ecosystems; that is, the difference between the NPP of potential vegetation (NPP_0) and the fraction of the NPP of the currently prevailing vegetation (NPP_{act}) that remains in the ecosystem after harvest (NPP_t) and is available for all other heterotrophic organisms:

$$\mathrm{HANPP} = \Delta \mathrm{NPP}_{LC} + \mathrm{NPP}_h = \mathrm{NPP}_0 - \mathrm{NPP}_t$$

In order to assess the HANPP in any particular region, one needs to quantify NPP_0, NPP_{act} and NPP_h. Subtracting NPP_h from NPP_{act} yields NPP_t which then allows to calculate HANPP as the difference between NPP_0 and NPP_t as indicated by the above formula. All papers assembled in this special issue are based on this definition. Some of the studies refer to total NPP (above- and belowground), some are restricted to the aboveground compartment. In the latter case the prefix "a" is used in order to make clear that the respective value only refers to the aboveground compartment (e.g., $aNPP_0$, $aNPP_{act}$, $aNPP_t$, aHANPP, etc.). HANPP can be expressed in absolute numbers as kilograms carbon per year (kg C/yr), as kilograms dry matter biomass per year (kg DM/yr) or as energy flow (Joules per year, J/yr). As a rough proxy one may assume that 1 t DM is equivalent to 0.5 t C and that the calorific value of dry matter biomass is around 18.5 Megajoules per kilogram (MJ/kg, 1 MJ $=10^6$ J).

The definition used here has the following advantages: (1) It strikes a good balance between being too restrictive and being too inclusive. It is inclusive enough to grasp the most relevant land use impacts such as agriculture, forestry and infrastructure. At the same time it is conservative because it explicitly accounts for the fraction of NPP remaining after harvest even in strongly human controlled ecosystems such as artificial grasslands, managed forests, or croplands. In such ecosystems, some of the NPP is used by wild-living organisms not controlled or used by humans, thus supporting some, in grasslands often even a very high, biodiversity. Thus, the definition of HANPP does not exaggerate human impact, as it only includes the amount of biomass actually harvested, on top of the NPP prevented by human land use. (2) It is robust in time series calculations. Land use sometimes reduces NPP, even prevents it altogether (as is the case with soil sealing), but technologies such as irrigation, fertilization or use of improved crop varieties may also raise NPP over its natural potential. Such effects are significant and historically variable, and should thus be included in comprehensive HANPP assessments. Natural dynamics such as changes in NPP_0 resulting from climate change are to be included as well (see below). By monitoring HANPP and its various components (NPP_{act}, NPP_t, and NPP_h), the impacts of different land use practices on the ecosystem energetics as well as their socioeconomic performance can be evaluated: land use may increase or reduce productivity, it may leave more or less energy in the ecosystem, it may yield rich or poor harvests, etc. We are thus also able to observe a possible decoupling of biomass harvest and HANPP (Krausmann, 2001).

3. Methodological issues in assessing HANPP

The consistent integration of a variety of databases is a prerequisite for establishing robust HANPP assessments. Datasets range from the ecological data, such as data on energy flows in natural and anthropogenic ecosystems, and data on vegetation cover, to data on the socioeconomic metabolism (Ayres and Simonis, 1994; Fischer-Kowalski et al., 1997; Matthews et al., 2000); for example, data on harvest and use of biomass products. Table 2 displays a systematic of the data groups, presents typical methodologies underlying data generation and gives some examples on data which have to be consistently merged in the HANPP assessments.

Data on material and energy flows (measured in kg dry matter, Joules, or kg carbon per year) have to be merged consistently with data on the extent of land use and land cover (measured in m², ha or km²) in order to yield plausible information on environmental pressures (in many cases measured in kg/m²/yr, e.g. agricultural biomass harvest), and in order to correspond with aggregates at higher spatial scales, that is, in order to match values recorded at the national level. Data integration, however, is made complex by the large discrepancy between the scales on which ecological processes and on which socioeconomic processes occur. Ecological processes depend on the interaction of a plethora of factors, e.g. of climate and soil parameters, at very small scales (e.g. the plot level), and thus require high-resolution spatially explicit data for their assessment. This renders remote sensing techniques and gridded datasets (rastered maps) suitable for their analysis. In contrast, many socioeconomic system interactions occur on a much higher spatial scale, e.g. on the level of political entities, such as municipalities, nation states or supranational formations, rendering the gridcell a very imperfect unit of analysis (Liverman et al., 1998). Nevertheless, data reconciliation for HANPP assessment requires the consistent integration of these different types of spatially explicit information. This is intricate, as large discrepancies still exist between census statistics on land use and data on land use/cover derived from remote sensing (Rindfuss et al., 2004; Erb et al., 2007; Goldewijk et al., 2007; Ramankutty et al., 2008).

Furthermore, data reconciliation is hampered by the fact that the datasets contain related but still different variables and reference units because they originate from different scientific disciplines and were gathered for different purposes. For example, the socioeconomic data on forestry usually document the mass (and value) of timber removed from forests, but do not or only partly report on economically less relevant biomass flows such as bark, branches or twigs. From an

Table 2
Data groups, main underlying methodologies and examples of data required for assessing HANPP.

	Spatially explicit data (rastered information)	Census data (administrative boundaries defined by socioeconomic systems)
Land use and land cover information	Remote sensing (e.g. Joint Research Center, 2002; FAO, 1999; Friedl et al., 2002; Hansen et al., 2003) Land use and land cover assessments (e.g. Erb et al., 2007; Ramankutty and Foley, 1998; Sanderson et al., 2002)	Census statistics/surveys (e.g. FAO, 2004; Eurostat, 2002) Cadastre surveys Forest inventories (e.g. FAO, 2001; UN, 2000)
Data on material and energy flows (in socioeconomic and ecological systems)	Dynamic vegetation models (e.g. results of the LPJ-DGVM, Sitch et al., 2003b)	Harvest statistics/surveys (e.g. FAO, 2004; Krausmann et al., 2008) Forest inventories (e.g. UN, 2000)

The references in brackets serve as examples and relate to the global assessment by Haberl et al. (2007).

HANPP perspective, nevertheless, a quantification of these flows is essential, as they have far-reaching ecological consequences (Nabuurs et al., 1997; Foley and Ramankutty, 2004; Lal, 2004; Wardle et al., 2004) and are therefore relevant as pressures on environmental systems. Moreover, for some socioeconomic activities no or very insufficient data exist. Grazing of domesticated livestock is one of the most prominent issues in this respect: Land use statistics on grazing land exist, but are known to be limited in scope and consistency (Harris, 2000; White et al., 2000; Ramankutty et al., 2006; Erb et al., 2007). Data on the amount of biomass grazed by livestock as well as on the amount of biomass harvested from grassland are practically non-existent in agricultural statistics. Thus, as for today, HANPP assessments have to rely on modelling techniques which consistently fill these and similar data gaps (Haberl et al., 2007; Krausmann et al., 2008).

A conceptual intricacy in the context of the HANPP assessments is related to wood harvest. Wood is accumulated in a forest over many years, so humans actually harvest the NPP accumulated over a period that is much longer than the current year. Subtracting such a harvest from NPP_0 may result in negative NPP_t values, even if averaged over larger regions, if stock-depleting forest management practices prevail. This is, although mathematically correct, counter-intuitive. In order to still produce plausible results, the papers assembled in this special issue allocate wood harvest not to the harvested plots alone, but to the entire forest area of the region under consideration, excluding untouched and wilderness areas. This procedure assumes that each plot of the entire forestry is harvested once during a full rotation cycle and this harvest is distributed equally across the whole forestry area under consideration. Kastner (2009) and Lauk and Erb (2009-this issue) discuss in more detail the intricacies resulting from this assumption. Another intricacy of HANPP assessments relates to the question how to deal with the remains of plants that are destroyed during harvest but not actually used by humans. Such remainders include crop residues that are not recovered as well as roots of crops or trees that are destroyed during harvest but not used. We here chose to include this biomass in the aggregate HANPP value, but explicitly report “unused extraction” or “backflows to nature” where appropriate.

HANPP quantifies the fraction of ecological energy flows diverted by humans. The basis of this assessment are estimates of the NPP of the potential vegetation. The notion of potential vegetation refers to the vegetation that would prevail in a defined area under current soil and climate conditions in the absence of human intervention (Tüxen, 1956). Dynamic vegetation models, such as the LPJ-DGVM (Lund-Potsdam-Jena Dynamic Vegetation Model; Sitch et al., 2003a; Gerten et al., 2005; Müller et al., 2006; Bondeau et al., 2007), are capable of modelling NPP flows in ecosystems on the basis of algorithms describing plant growth as a function of plant competition and climate variables such as temperature, water availability and CO_2 content of the atmosphere in a spatially explicit way and with a high level of agreement between different models (Cramer et al., 1999; Cramer et al., 2001; Saugier et al., 2001). The definition of the potential vegetation as a function of the currently prevailing soil and climate conditions entails that — when applied in a time series analysis — NPP_0 must not be regarded as a static parameter, but as a dynamic variable: In particular, the rise of the atmospheric CO_2 during the last centuries — e.g. as a consequence of the anthropogenic fossil fuel combustion —is known to have resulted in an increase of NPP, also denoted as the “CO_2-fertilization effect” (Schimel, 1995), even though there is discordance on the strength of this effect (Norby and Yiqi, 2004).

To take this and other climate change effects into account, a model run by the LPJ-DGVM in a time series was performed, providing consistent information on the changes in the national NPP_0 over time for all articles in this special issue that present time series analyses. For this assessment, gridded historical monthly climate data between 1901 and 2003 were extrapolated backwards to 1700 based on results from the Climber Model (New and Hulme, 2000; Österle and Gerstengarbe, 2003; Mitchell and Jones, 2005). NPP_0 was calculated at 0.5° spatial resolution, using these climate data and a soil-type classification at the same resolution as input data. LPJ was then run for the period 1700–2002 after a spin up of 900 years for the first 3 decades of the 18th century to reach an equilibrium. For the national NPP_0 time series, the 30 yr average of the results was used in order to eliminate data artefacts and small-scale fluctuations resulting from the extrapolation procedure. It should be noted that the dynamic NPP_0 results do not only refer to the potential vegetation, but are relevant also for certain NPP_{act} parameters. For example, in the absence of better data, the NPP of pristine forests is assumed to be equal to forest subjected to management (Haberl et al., 2007), and thus the NPP_{act} of forests in time series follows the trend of NPP_0.

4. Drivers and processes: an overview on the articles that follow

The intricate interplay of the proximate and underlying factors which influence temporal and spatial patterns of HANPP is best analyzed through time series analyses at a reasonably small scale, e.g. for a nation state (Krausmann and Haberl, 2002; Krausmann et al., 2003; Krausmann, 2004; Krausmann and Haberl, 2007). Four of the papers assembled in this special issue present such detailed analyses at the country level.

In the first paper, Kastner (2009) investigates the development of aboveground HANPP in the Philippines during a one hundred year period since the beginning of the 20th century. While all other existing HANPP case studies focus on industrialized European countries, this paper presents a first assessment for a less developed Asian country. During the observed period, the Philippines experienced tremendous population growth and developed from a sparsely populated country (28 cap/km² in 1910) to one of the most densely populated countries in the world (275 cap/km² in 2000). The demographic development, enforced by the expansion of an export-oriented agriculture and forestry sector, was accompanied by massive deforestation, an expansion of agricultural land and changes in the intensity of agriculture. As a result, a steep increase of HANPP from about 30% in 1910 to about 60% in 1970 could be observed. From the 1960s onwards, the efforts of the Green Revolution lead to remarkable gains in land use efficiency and buffered the effects of population growth, and in the 1970s the industrialization of agriculture and the increasing reliance on agricultural imports stabilized aHANPP at a comparatively high level. The paper by Kastner not only impressively shows the combined effect of population pressure, changes in land use intensity and trade patterns on HANPP, it also addresses important conceptual issues related to the representation of slash-and-burn agriculture in the HANPP calculations.

The paper by Musel (2009) presents aHANPP in the United Kingdom, spanning the time period from 1800 to the year 2000. The UK is indeed an important case as it is the global forerunner of industrialization, and despite its enormous length, this time series does not cover the whole agrarian–industrial transition that had in the UK already started in the 17th century. Within these 200 years, the population of the UK increased 3.8-fold, the aggregate GDP by a factor of approximately 44 and per capita GDP by a factor of slightly below 12 (Maddison, 2001). Aboveground HANPP, by contrast, declined a bit from 71% in 1800 to 68% in the year 2000 — despite an increase of annual biomass harvest ($aNPP_h$) per hectare of 69%. The paper by Musel gives a fascinating account of how the UK managed to cope with area limitations through agricultural intensification and increased reliance on imports. Quite remarkably, $aNPP_{act}$ even surpasses $aNPP_0$ in the UK towards the end of the study period (thereby resulting in negative $\Delta aNPP_{LC}$ values), due to heavy reliance on fossil-fuel based inputs such as machinery and fertilizers. Such a situation is globally exceptional even today (Haberl et al., 2007). Musel's paper forcefully supports the notion that the agrarian–

industrial transition results in stunning increases in area-efficiency of land use systems at the price of an increased reliance on unsustainable input factors directly or indirectly derived from fossil fuels.

This pattern is corroborated by Schwarzlmüller (2009-this issue) for a Mediterranean country, in this case through a study of the aboveground HANPP of Spain from 1955 to 2003. He finds that aHANPP declined in Spain from 67% of $aNPP_0$ in 1955 to 61% in 2003, despite an 8.4-fold increase in GDP and a 1.47-fold increase in population. Schwarzlmüller argues that most of the industrialization of Spain's agriculture occurred within the studied time period and he gives impressive figures of the increase in fossil fuel and electricity consumption in Spanish agriculture associated with this transition. He demonstrates that the land use related productivity loss was dramatic in Spain in 1955 and was reduced quite considerably due to agricultural intensification within the studied period thereafter. Nevertheless, $\Delta aNPP_{LC}$ was still at a remarkably high level in Spain as compared to other European countries — a fact that can well be explained by Spain's climatic and geomorphologic conditions as well as the high intensity of historic land use (Latorre et al., 2001) and consequent soil degradation (see also Zika and Erb, 2009-this issue). Again, both the increase in forest area and increased $aNPP_{act}$ on cropland contribute to the decline in ΔNPP_{LC}. Spain succeeded in increasing biomass harvest ($aNPP_h$) by as much as 56% in less than 50 years — an impressive example of the efficiency increases associated with the industrialization of agriculture.

With their case study on Hungary, a country where intensively used agricultural land covers more than two thirds of the territory, Kohlheb and Krausmann (2009-this issue) present a first HANPP study of a centrally planned economy. They reconstruct the development of land use, biomass harvest and aHANPP since the early 1960s. During this period, the country experienced radical political and economic change. For five decades, Hungary was a centrally planned economy until the communist regime collapsed in 1989, and Hungary turned into a Western market economy, joining the European Union in 2004. The paper shows how during the centrally planned period rapid collectivisation and capital investments drove the industrialization of Hungarian agriculture, boosted yields and turned Hungary into a biomass exporting country. Very much like the development that has been observed in market economies such as the UK (Musel, 2009), Austria (Krausmann, 2001) or Spain (Schwarzlmüller, 2009-this issue) during the second half of the 20th century, in Hungary a surge in biomass output was associated with a drastic decline of the initially very high HANPP, among others driven by the reforestation of land of marginal agricultural productivity. The collapse of the communist regime had a devastating effect on the economy and agriculture. Between 1989 and 1993, GDP slumped by 21%, biomass harvest by 39% and aHANPP temporarily even increased. It took several years until after the massive structural changes the productivity of Hungarian agriculture began to increase again.

A second group of papers is dedicated to the analysis and quantification of parameters contributing to global HANPP for which currently no or only extremely limited data exist. In their contribution, Lauk and Erb (2009-this issue) analyze the magnitude and geographic pattern of human-induced vegetation fires in the year 2000. Vegetation fires destroy a large amount of biomass and constitute an important human interference in the energy flows of the terrestrial ecosystems. They are thus highly relevant in the HANPP context. Applying model assumptions on the area extent and rotation cycle of slash-and-burn agriculture, the data gaps related to (small) vegetation fires due to shifting cultivation could be closed and brought into an estimate of the loss of biomass caused globally by large vegetation fires, the latter based on published data. 85% of all vegetation fires are caused by human activities, in particular by slash-and-burn activities which amount to 1–1.4 billion tons of dry matter biomass burned each year. An additional 0.45 billion tons per year are most likely to be destroyed by burning of cropland residues in the field (Yevich and Logan, 2003; this figure, however, refers to the year 1985 and is thus of indicative value only). In total, 4.4 billion tons of dry matter biomass are consumed each year in human-induced fires; a flow equivalent to 14% to the global HANPP of in the year 2000 as estimated by Haberl et al. (2007). These results illustrate the importance of this aspect of society–nature interaction. Human-induced vegetation fires are particularly important in developing countries, such as Sub-Saharan Africa, Latin America and South-Eastern Asia, whereas in industrial countries vegetation fires play a less significant role in terms of HANPP. Lauk and Erb show that the current spatial patterns of biomass burning can largely be explained by a nation's degree of industrialization and population density. This is due to the fact that vegetation fires are used as an effective land use tool, whose importance declines in case of land scarcity or the availability of other means to prevent soil degradation by artificial input into the land system, such as fertilizer and mechanical power.

Another land use aspect of global scope is presented by Zika and Erb (2009-this issue). They study in detail the productivity losses (ΔNPP_{LC}) resulting from degradation in drylands, also denoted as 'desertification'. Dryland degradation, i.e. the temporary or permanent reduction in the productive capacity of land situated in dry climates meets with a lack of global data and homogeneous definitions, despite its acknowledged role as an environmental and development issue of global importance. By combining the best available data on the extent of dryland degradation and its degree in a geographic information system, the authors produce two independent estimates of the productivity losses caused by dryland degradation, one based on simple assumptions of NPP losses per degradation degree, the second one making use of gridded data on agricultural productivity. NPP losses were found to range between 799 and 1 936 TgC/yr, or 4% to 10% of the potential NPP in drylands; this amounts to 20–40% of the potential NPP on degraded agricultural areas. In some regions, the effect of dryland degradation on HANPP is found to be of similar magnitude as the overall annual socioeconomic biomass harvest, which once more highlights the need to take productivity losses (ΔNPP_{LC}) in HANPP assessments explicitly into account. As a large share of the global human population is affected by dryland degradation, the restoration of degraded land is highly desirable, in particular in the light of the forecasted population growth rates in these regions.

The paper by O'Neill and Abson (2009) adds another facet by demonstrating that HANPP can be used to analyze important spatial patterns of global human activities. They test, at the global scale, the hypothesis that settlements are predominantly located in highly productive areas whereas protected areas (parks and other conservation areas) are predominantly located in areas with lower biological productivity. They combine spatially explicit datasets of settlement areas and parks (in the IUCN categories I–VI) with the global HANPP dataset of Haberl et al. (2007). Their analysis unequivocally confirms the first hypothesis: Humans do indeed prefer to inhabit areas with a considerably higher-than-average productivity. The second hypothesis is not supported at the global scale (parks are found to have roughly average productivity) but is supported in some world regions, especially in North America. O'Neill and Abson also find that HANPP in parks increases as management category according to IUCN rules becomes less restrictive. They demonstrate that HANPP and its components may provide valuable additional information for evaluating the extent and effectiveness of global conservation networks.

Erb and colleagues (2009-this issue) present an assessment of the global spatial disconnect between biomass production and one of its most important drivers, biomass consumption, based on an extension of the HANPP accounting framework. Due to trade, products derived from using the land are seldom used where they are produced, resulting in a growing separation between the production and consumption of biomass. As a consequence, pressures on ecosystems visible in some areas can stem from the consumption of products in far distant locations. By comparing global maps of HANPP and embodied HANPP, i.e. the mass of upstream NPP flows associated with the consumption of biomass goods, they show the magnitude and spatial pattern of this disconnect in a cross-scale analysis. According to their study, international net transfers of embodied HANPP amount to 1.7 PgC/yr, a significant flow when compared e.g. to global carbon emissions from industrial processes (c.7.6 PgC/yr) or the current total annual global net emissions of carbon stemming from land use change (mostly deforestation) of 1.5 PgC/yr (Canadell et al., 2007). The location and the extent of producing and consuming areas indicate that the flow of embodied HANPP bridges considerable distances. Embodied HANPP predominantly flows from sparsely populated to densely populated regions. Large regions are still not participating in this global exchange. The paper stresses the importance of a better understanding of these "teleconnections", as globalization and urbanization are processing fast, and result in a high degree of cross-regional interdependence, with unknown consequences for the resilience of socio-ecological systems. Lastly, the paper underlines the need to sustainably manage supply and demand of products of the ecosystems on a global level.

5. Conclusion and outlook

NPP is a key resource of the coupled socio-ecological systems. It is a vital parameter of the ecosystem functioning, and, at the same time, the basis of the provision of the biomass products to society, which constitutes an essential fraction of the socioeconomic metabolism that is by and large not substitutable by man-made capital (Ayres, 2007). The articles assembled in this special issue illustrate the ability of the HANPP concept to link natural and socioeconomic processes and to generate an integrated picture of socio-ecological conditions, a major goal of sustainability science (Kates et al., 2001; Kates and Parris, 2003).

The amount of NPP diverted and altered by human activities is the outcome of the interplay of natural and socioeconomic factors. How these factors determine spatial patterns and temporal dynamics of HANPP is at present only poorly understood. Whereas it is possible to identify, quantify and even map certain "proximate causes" (Lambin and Geist, 2006) of HANPP, such as cropland agriculture, livestock rearing, land-take by infrastructure and urbanization, or forestry, it is much more difficult to depict the relation of these factors to underlying processes such as economic growth, increasing trade volumes, energy supply patterns, population growth and changes in agricultural technology (Krausmann et al., 2009). The results of the time series analyses by Kastner, Musel, Schwarzlmueller, and Kohlheb and Krausmann highlight the intricate interplay of the demand for biomass products, land use and land use intensity. The studies underline that no single factor is able to explain patterns, dynamics and magnitude of national HANPP. Population (density) and the demand for biomass certainly play a strong role. Nevertheless, these factors are influenced by climatic conditions, development status and the degree of the integration in world markets, and superimposed by technological developments and capacity. Dietary patterns and characteristics of the livestock system (e.g., livestock density or feed conversion efficiency) certainly also play a decisive role. All these interdependencies result in a complex interplay of causes and effects, and factor bundles that amplify, counteract or superimpose each other in shaping the trajectory of HANPP and its components in a region.

It is obvious that the socioeconomic demand for biomass products is a major driver of the human appropriation of NPP. However, no simple relation of biomass demand and HANPP can be put forward at present. The interrelation between biomass demand and HANPP is determined by a number of "conversion" or "efficiency" factors (Fig. 2): First, the production of one unit of biomass products for final consumption requires a varying amount of primary biomass input into the socioeconomic system (used extraction), depending on the

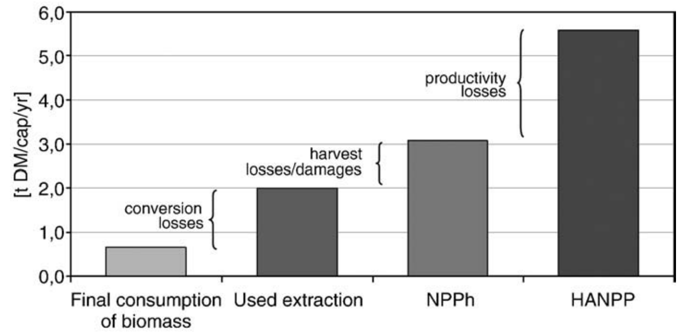

Fig. 2. The interrelation between final biomass demand and HANPP, and related "conversion losses". The presented values refer to the global biomass flows in t dry matter per capita in the year 2000, as assessed in Haberl et al. (2007), Krausmann et al. (2008) and Krausmann et al. (2009).

conversion losses of the livestock sector or the food-producing industry. Thus, the mix of socioeconomic biomass demand, in particular the proportion between consumption of animal-based and vegetable-based biomass is decisive, because in general animal-based products are associated with much smaller conversion efficiencies. Second, the amount of biomass extracted and used in the socioeconomic system is associated with a varying amount of harvest losses (unused extraction), which mainly depends on factors such as the land use technology and the type of biomass. Used and unused extraction sum up to NPP_h. And third, the amount of HANPP resulting from NPP_h is again highly variable, depending on factors such as land use technology, the type of ecosystem under use, the ability to avoid land degradation, i.e. to keep agricultural yields high despite massive losses of soil nutrients. This last "conversion" rate encloses productivity losses due to land conversion (ΔNPP_{LC}).

Consequently, the amount for biomass products and its associated national HANPP depends on a number of interrelated factors: a) the composition of national biomass demand (e.g animal vs. vegetable biomass); b) technology and the prevailing agricultural and forestry productions system(s) in a country and, c) the integration into the global economy and international trade with agricultural products, where biomass demand can be covered from resources outside the national territory (Erb et al., 2009-this issue).

Nevertheless, the empirical results presented in this special issue suggest that, despite the differences in population, population density, economic and technological status, land use systems and historical developments, common patterns in the development of HANPP through time exist: Agricultural intensification, via increases of the efficiency of biomass appropriation per unit area (i.e. reduction of the amount of HANPP per NPP_h), is capable to compensate for surges in biomass demand and increases in the share of animal protein in human diets. This implies that the growth of HANPP is mostly far lower than the growth of biomass demand — HANPP may even decline while biomass harvest grows. In the European case studies, the effect of agricultural intensification, mainly input-driven, is often more than strong enough to counterbalance the effect of surging biomass harvests. In the Philippines (Kastner, 2009), by contrast, HANPP almost doubled during the observed period. Nevertheless, the strong increase of human pressure on the nation's ecosystems was by far smaller than the 10-fold increase in population.

The efficiency gains that result from intensification and industrialization of agricultural practices — enabling for increased harvests at more or less stabilized HANPP — seems to be a common feature in different historical settings. This entails that the concept of "carrying capacity" in the human–environment context cannot be assessed on the basis of simple quantitative land use parameters, such as the area of land under use. Instead, the sustainability question is strongly related to the amount of land as well as the intensity with which the land is used, and the ability of the natural systems to cope with this land use intensity. HANPP allows moving beyond oversimplified "footprint" approaches by relating socioeconomic activities and metabolism to the intensity of land use and ecosystem functioning, thereby contributing to a more differentiated perspective.

The articles assembled in this special issue underline the need to advance our understanding of the coupled Earth System and its multiple facets, as well as the urgent need to improve and extend the databases on vital, but currently neglected, society–nature interactions. By applying the HANPP concept for analyses of the extent, pattern and magnitude of dryland degradation and human-induced fires, these studies demonstrate the analytical potential of HANPP, and at the same time illustrate how limited our current understanding of the essential aspects of the coupled Earth System is. The high potential of HANPP studies as a tool to inform land use management is illustrated by the contribution of O'Neill and Abson, which tests the suitability of the HANPP indicator for nature conservation planning. The papers also illustrate that national economies cause HANPP not only within their own territory but also beyond their boundaries, through biomass imports (see Erb et al., 2009-this issue). At the same time, the production of exported goods contributes to HANPP on their own territory (see also Kastner, 2009). The currently accelerating integration of global markets superimposes the relation between patterns of national biomass demand and HANPP and creates a further sustainability challenge by increasing the spatial disconnect of biomass consumption and land use (Chisholm, 1990; Turner et al., 2007; Erb et al., 2009-this issue).

The research presented here confirms the value of HANPP as an indicator of strong sustainability, emphasizing the non-substitutability of natural capital by human-made capital (Meadows et al., 1992; Sagoff, 1995; Martinez-Alier, 1998; Martinez-Alier, 1999; Costanza et al., 1998). NPP, although partially replaceable by e.g. fossil fuel derived products, is practically not substitutable as it is the only source of food to humans and closely connected to the provision of the essential ecosystem services such as buffering and purifying services (Daily et al., 1997; Millennium Ecosystem Assessment, 2005; Ayres, 2007). Moreover, the contributions assembled in this special issue suggest that the indicator HANPP can help to analyze the complex interrelations between the socioeconomic systems and their natural environment in a truly interdisciplinary manner, linking approaches from economics, ecology and other social and natural sciences.

New, innovative tools that are capable of capturing the within-scalar and cross-scalar spatio-temporal dynamics of land use need to be developed. Extensions of the HANPP concept, which quantify the HANPP embodied in biomass products, could provide valuable information on sustainability aspects of socio-ecological systems, linking drivers and impacts of land use. This would be relevant for assessments of the provision of biomass for food, feed and fibres, and energy, and analyses of the trade-offs between different uses of biomass. Recent policies in many industrialized countries aimed at fostering the use of biofuels (Goldemberg, 2000; Fischer et al., 2009) render such research particularly relevant. It is common knowledge today that bioenergy provision could come at high environmental costs (Field et al., 2008; Fargione et al., 2008), mainly depending on the selected technological path and type of biomass used. Accounts of HANPP embodied in bioenergy products could provide further, complementary information of the sustainability aspects related to such strategies.

Acknowledgements

We thank Wolfgang Lucht, Joan Martínez-Alier, Christoph Plutzar, Anette Reenberg, and Helga Weisz for discussions and collaboration. This article draws from research funded by the Austrian Science Fund (FWF) within the projects P16692-G05 and P20812-G11, which is gratefully acknowledged, and contributes to A Long-Term Biodiversity, Ecosystem and Awareness Research Network (ALTER-Net, http://www.alter-net.info), and the Global Land Project (http://www.globallandproject.org).

References

Andreae, M.O., McManus, L., Matson, P.A., 2004. Anthropogenic Modification of Land, Coastal, and Atmospheric Systems as Threats to the Functioning of the Earth System. In: Schellnhuber, H.-J., Crutzen, P.J., Clark, W.C., Claussen, M., Held, H. (Eds.), Earth System Analysis for Sustainability. The MIT Press, Cambridge, M.A., pp. 245–264.
Ayres, R.U., 2007. On the practical limits to substitution. Ecological Economics 61 (1), 115–128.
Ayres, R.U., Simonis, U.E., 1994. Industrial Metabolism: Restructuring for Sustainable Development. United Nations University Press, Tokyo.
Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Muller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13 (3), 679–706.
Canadell, J.G., Le Quere, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T. J., Gillett, N.P., Houghton, R.A., Marland, G., 2007. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences of the USA 104, 18866–18870.
Chisholm, M., 1990. The Increasing Separation of Production and Consumption. In: TurnerII II, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B. (Eds.), The Earth as Transformed by Human Action. Cambridge University Press, Cambridge, pp. 87–102.
Cohen, J.E., 1995. How Many People Can the Earth Support? W. W. Norton & Company, New York.
Costanza, R., Cumberland, J., Daly, H.E., Goodland, R., Norgaard, R.B., 1998. An Introduction to Ecological Economics. CRC Press, Boca Raton, FL/USA.
Cramer, W., Kicklighter, D.W., Bondeau, A., Moore III, B., Churkina, G., Nemry, B., Ruimy, A., Schloss, A., Kaduk, J., The Participants of the Potsdam NPP Model Intercomparison, 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Global Change Biology 5 (Issue S1), 1–15.
Cramer, W., Olson, R.J., Prince, S.D., Scurlock, J.M.O., Members of the Global Primary Production Data Initiative, 2001. Determining Present Patterns of Global Productivity. In: Roy, J., Saugier, B., Mooney, H.A. (Eds.), Terrestrial Global Productivity. Academic Press, San Diego, pp. 429–448.
Crutzen, P.J., Steffen, W., 2003. How long have we been in the anthropocene era? Climatic Change 61 (3), 251–257.
Daily, G.C., Alexander, S., Ehrlich, P.R., Goulder, L., Lubchenco, J., Matson, P.A., Mooney, H.A., Postel, S.L., Schneider, S.H., Tilman, D., Woodwell, G.M., 1997. Ecosystem Services: Benefits Supplied to Human Societies by Natural Ecosystems. Issues in Ecology 2, 1–18.
Davidson, C., 2000. Economic Growth and the Environment: Alternatives to the Limits Paradigm. BioScience 50 (5), 433–440.
DeFries, R.S., Field, C.B., Fung, I., Collatz, G.J., Bounoua, L., 1999. Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. Global Biogeochemical Cycles 13 (3), 803–815.
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.
Ellis, E.C., Ramankutty, N., 2008. Putting People in the Map: Anthropogenic Biomes of the World. Frontiers in Ecology and the Environment 6, 439–447.
Erb, K.-H., Krausmann, F., Lucht, W., Haberl, H., 2009. Embodied HANPP: Mapping the spatial disconnect between global biomass production and consumption. Ecological Economics 69, 328–334 (this issue).
Erb, K.-H., Gaube, V., Krausmann, F., Plutzar, C., Bondeau, A., Haberl, H., 2007. A comprehensive global 5min resolution land-use dataset for the year 2000 consistent with national census data. Journal of Land Use Science 2 (3), 191–224.
Eurostat. Eurostat New Cronos. Macroeconomic and social statistical data. Internet. 2002. Luxembourg, European Communities.
FAO, 1999. Global forest cover map. FAO, Rome.
FAO, 2001. Global Forest Resources Assessment 2000. Main report. FAO, Rome.
FAO, 2004. FAOSTAT 2004, FAO Statistical Databases: Agriculture, Fisheries, Forestry, Nutrition. FAO, Rome.
FAO, 2005. The State of Food Insecurity in the World 2005. Eradicating world hunger - key to achieving the Millennium Development Goals. Food and Agriculture Organization of the United Nations, Rome.
Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land Clearing and the Biofuel Carbon Debt. Science 319 (5867), 1235–1238.
Field, C.B., 2001. Sharing the Garden. Science 294, 2490–2491.
Field, C.B., Campbell, J.E., Lobell, D.B., 2008. Biomass energy: the scale of the potential resource. Trends in Ecology & Evolution 23 (2), 65–72.
Fischer, G., Hizsnyik, E., Prieler, S., Shah, M., Velthuizen, H.v., 2009. Biofuels and Food Security. OPEC Fund for International Development (OFID. International Institute for Applied Systems Analysis (IIASA, Vienna, Laxenburg, Austria.
Fischer-Kowalski, M., Haberl, H., Hüttler, W., Payer, H., Schandl, H., Winiwarter, V., Zangerl-Weisz, H., 1997. Gesellschaftlicher Stoffwechsel und Kolonisierung von Natur. Ein Versuch in Sozialer Ökologie. Gordon & Breach Fakultas, Amsterdam.
Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use. Science 309 (5734), 570–574.

Foley, J.A., Ramankutty, N., 2004. A primer on the terrestrial carbon cycle: What we don't know but should. In: Field, C.B., Raupach, M.R. (Eds.), The Global Carbon Cycle. Integrating Humans, Climate, and the Natural World. SCOPE 62. Island Press, Washington, D.C., pp. 279–294.

Friedl, M.A., McIver, D.K., Hodges, J.C.F., Zhang, X.Y., Muchoney, D., Strahler, A.H., Woodcock, C.E., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F., Schaaf, C., 2002. Global land cover mapping from MODIS: algorithms and early results. Remote Sensing of Environment 83 (1–2), 287–302.

Gaston, K.J., 2000. Global patterns in biodiversity. Nature 405, 220–227.

Gerten, D., Hoff, H., Bondeau, A., Lucht, W., Smith, P., Zaehle, S., 2005. Contemporary "green" water flows: Simulations with a dynamic global vegetation and water balance model. Physics and Chemistry of the Earth, Parts A/B/C 30 (6–7), 334–338.

GLP, 2005. Global Land Project. Science Plan and Implementation Strategy. IGBP Secretariat, Stockholm.

Goldemberg, J., 2000. World Energy Assessment. Energy and the Challenge of Sustainability. United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council, New York.

Goldewijk, K.K., Van Drecht, G., Bouwman, A.F., 2007. Mapping contemporary global cropland and grassland distributions on a 5×5 minute resolution. Journal of Land Use Science 2 (3), 167–190.

Haberl, H., 1997. Human Appropriation of Net Primary Production as an Environmental Indicator: Implications for Sustainable Development. Ambio 26 (3), 143–146.

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

Haberl, H., Erb, K.-H., Krausmann, F., Loibl, W., Schulz, N.B., Weisz, H., 2001. 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., Gaube, V., Díaz-Delgado, R., Krauze, K., Neuner, A., Peterseil, J., Singh, S.J., Vadineanu, A., 2009. Towards an integrated model of socioeconomic biodiversity drivers, pressures and impacts. A feasibility study based on three European long-term socio-ecological research platforms. Ecological Economics 68 (6), 1797–1812.

Haberl, H., Krausmann, F., Erb, K.-H., Schulz, N.B., Rojstaczer, S., Sterling, S.M., Moore, N., 2002. Human Appropriation of Net Primary Production. Science 296, 1968–1969 (14. June).

Haberl, H., Plutzar, C., Erb, K.-H., Gaube, V., Pollheimer, M., Schulz, N.B., 2005. Human Appropriation of Net Primary Production as Determinant of Avifauna Diversity in Austria. Agriculture, Ecosystems & Environment 110 (3–4), 119–131.

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 10 (3), 177–191.

Haberl, H., Schulz, N.B., Plutzar, C., Erb, K.-H., Krausmann, F., Loibl, W., Moser, D., Sauberer, N., Weisz, H., Zechmeister, H.G., Zulka, P., 2004a. Human Appropriation of Net Primary Production and Species Diversity in Agricultural Landscapes. Agriculture, Ecosystems & Environment 102 (2), 213–218.

Haberl, H., Wackernagel, M., Wrbka, T., 2004b. Land Use and Sustainability Indicators. Special issue of *Land Use Policy* 21(3), 193-320. Pergamon / Elsevier, Oxford.

Hannah, L., Lohse, D., Hutchinson, C., Carr, J.L., Lankerani, A., 1994. A Preliminary Inventory of Human Disturbance of World Ecosystems. Ambio 23 (4–5), 246–250.

Hansen, M.C., DeFries, R.S., Townshend, J.R.G., Carroll, M., Dimiceli, C., Sohlberg, R.A., 2003. Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS vegetation continous field algorithm. Earth Interactions 7 (10), 1–15.

Harmon, M.E., Ferrell, W.K., Franklin, J.F., 1990. Effects on Carbon Storage of Conversion of Old-Growth Forests to Young Forests. Science 247, 699–702.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15, 133–302.

Harris, P.S., 2000. Grassland resource assessment for pastoral systems. Food and Agricultural Organization of the United Nations (FAO), Rome.

Heywood, V.H., Watson, R.T., 1995. Global Biodiversity Assessment. Cambridge University Press, United Nations Environment Programme (UNEP), Cambridge.

Holling, C.S., 1973. Resilience and Stability of Ecological Systems. Annual Review of Ecological Systematics 4, 1–24.

Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., Lawrence, W.T., 2004. Global patterns in human consumption of net primary production. Nature 429 (6994), 870–873.

Joint Research Center, 2002. Global Land Cover 2000 (GLC2000). http://www-gvm.jrc.it/glc2000/.

Kastner, T., 2009. Trajectories in human domination of ecosystems: Human appropriation of net primary production in the Philippines during the 20th century. Ecological Economics 69, 260–269.

Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grübler, A., Huntley, B., Jäger, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P.A., Mooney, P., Mooney, H.A., Moore III, B., O'Riordan, T., Svedin, U., 2001. Environment and Development: Sustainability Science. Science 292, 641–642.

Kates, R.W., Parris, T.M., 2003. Science and Technology for Sustainable Development Special Feature: Long-term trends and a sustainability transition. Proceedings of the National Academy of Sciences of the United States of America 100 (14), 8062–8067.

Kay, J.J., Regier, H.A., Boyle, M., Francis, G., 1999. An Ecosystem Approach for Sustainability: Addressing the Challenge of Complexity. Futures 31 (7), 721–742.

Kohlheb, N., Krausmann, F., 2009. Land use change, biomass production and HANPP:The case of Hungary 1961-2005. Ecological Economics 69, 292–300 (this issue).

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., 2004. Milk, Manure and Muscular Power. Livestock and the Industrialization of Agriculture. Human Ecology 32 (6), 735–773.

Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., Haberl, H., 2008. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. Ecological Economics 65 (3), 471–487.

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., 2007. Land-use change and socio-economic metabolism. A macro view of Austria 1830–2000. In: Fischer-Kowalski, M., Haberl, H. (Eds.), Socioecological transitions and global change: Trajectories of Social Metabolism and Land Use. Edward Elgar, Cheltenham, UK, Northampton, pp. 31–59.

Krausmann, F., Haberl, H., Erb, K.-H., Wiesinger, M., Gaube, V., Gingrich, S., 2009. What determines geographical patterns of the global human appropriation of net primary production? Journal of Land Use Science 4 (1), 15–34.

Krausmann, F., Haberl, H., Schulz, N.B., Erb, K.-H., Darge, E., Gaube, V., 2003. Land-use change and socio-economic metabolism in Austria. Part I: driving forces of land-use change: 1950-1995. Land Use Policy 20 (1), 1–20.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123 (1–2), 1–22.

Lambin, E.F., Geist, H.J., 2006. Land-Use and Land-Cover Change. Local Processes and Global Impacts. Springer, Berlin.

Latorre, J.G., Latorre, J.G., Sanchez-Picón, A., 2001. Dealing with aridity: socio-economic structures and environmental changes in an arid Mediterranean region. Land Use Policy 18 (1), 53–64.

Lauk, C., Erb, K.-H., 2009. Biomass consumed in anthropogenic vegetation fires: global patterns and processes. Ecological Economics 69, 301–309 (this issue).

Lindeman, R.L., 1942. The Trophic-Dynamic Aspect of Ecology. Ecology 23 (4), 399–417.

Liverman, D., Moran, E.F., Rindfuss, R.R., Stern, P.C., 1998. People and Pixels, Linking Remote Sensing and Social Science. National Academy Press, Washington DC.

Maddison, A., 2001. The World Economy. A millenial perspective. OECD, Paris.

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

Martinez-Alier, J., 1999. The Socio-ecological Embeddedness of Economic Activity: The Emergence of a Transdisciplinary Field. In: Jahn, T., Becker, E. (Eds.), Sustainability and the Social Sciences. Zed Books, London, pp. 112–139.

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

McGuire, A.D., Sitch, S., Clein, J.S., Dargaville, R., Esser, G., Foley, J.A., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D.W., Meier, R.A., Melillo, J.M., Moore III, B., Prentice, I.C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L.J., Wittenberg, U., 2001. Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO2, climate and land-use effects with four process-based ecosystem models. Global Biogeochemical Cycles 15 (1), 183–206.

Meadows, D.L., Meadows, D.H., Randers, J., 1972. The Limits to Growth. Universe Books, New York.

Meadows, D.L., Meadows, D.H., Randers, J., 1992. Beyond the Limits: Global Collapse or a Sustainable Future. Earthscan, London.

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

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25 (6), 693–712.

Müller, C., Bondeau, A., Lotze-Campen, H., Cramer, W., Lucht, W., 2006. Comparative impact of climatic and nonclimatic factors on global terrestrial carbon and water cycles. Global Biogeochemical Cycles 20 (GB4015), 1–13.

Musel, A., 2009. Human appropriation of net primary production in the United Kingdom, 1800 – 2000. Changes in society's impact on ecological energy flows during the agrarian-industrial transition. Ecological Economics 69, 270–281.

Nabuurs, G.J., Paivinen, R., Sikkema, R., Mohren, G.M.J., 1997. The role of European forests in the global carbon cycle–A review. Biomass and Bioenergy 13 (6), 345–358.

New, M., Hulme, M., 2000. Representing twentieth century space-time climate variability. II: Development of 1901–1996 monthly grids of terrestrial surface climate. Journal of Climate 13, 2217–2238.

Norby, R.J., Yiqi, L., 2004. Evaluating ecosystem responses to rising atmospheric CO_2 and global warming in a multi-factor world. New Phytologist 162 (2), 281–293.

O'Neill, D.W., Abson, D.J., 2009. To settle or protect? A global analysis of net primary production in parks and urban areas. Ecological Economics 69, 319–327.

Österle, H. and Gerstengarbe, F.-W. Homogenisierung und Aktualisierung des Klimadatensatzes des Climate Research Unit der Universität of East Anglia, Norwich. 6. Deutsche Klimatagung 2003. Potsdam, Germany.

Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochemical Cycles 22 (GB1003). doi:10.1029/2007GB002952-.

Ramankutty, N., Foley, J.A., 1998. Characterizing patterns of global land use: an analysis of global croplands data. Global Biogeochemical Cycles 12 (4), 667–685.

Ramankutty, N., Graumlich, L., Achard, F., Alves, D., Chhabra, A., DeFries, R.S., Foley, J.A., Geist, H.J., Houghton, R.A., Klein Goldewijk, K., Lambin, E., Millington, A., Rasmussen, K., Reid, R.S., Turner II, B.L., 2006. Global land-cover change: Recent progress, remaining challenges. In: Lambin, E.F., Geist, H.J. (Eds.), Land-use and land-cover change. Local processes and global impacts. Springer, Berlin, pp. 9–39.

Rindfuss, R.R., Walsh, S.J., Turner II, B.L., Moran, E.F., Entwisle, B., 2004. Linking Pixels and People. In: Gutman, G., Janetos, A.C., Justice, C.O., Moran, E.F., Mustard, J.F., Rindfuss, R.R., Skole, D., TurnerII II, B.L., Cochrane, M.A. (Eds.), Land change science. Observing, monitoring and understanding trajectories of change on the Earth's surface. Kluwer, Dordrecht, pp. 379–394.

Rojstaczer, S., Sterling, S.M., Moore, N., 2001. Human Appropriation of Photosynthesis Products. Science 294 (5551), 2549–2552.

Sagoff, M., 1995. Carrying capacity and ecological economics. BioScience 45 (9), 610–620.

Sanderson, E., Jaiteh, M., Levy, M., Redford, K., Wannebo, A., Woolmer, G., 2002. The human footprint and the last of the wild. BioScience 52 (10), 891–904.

Saugier, B., Roy, J., Mooney, H.A., 2001. Estimations of Global Terrestrial Productivity: Converging toward a Single Number? In: Roy, J., Saugier, B., Mooney, H.A. (Eds.), Terrestrial Global Productivity. Academic Press, San Diego, pp. 543–557.

Schimel, D., 1995. Terrestrial ecosystems and the carbon cycle. Global Change Biology 1 (1), 77–91.

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003a. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Global Change Biology 9 (2), 161–185.

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kamplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003b. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Global Change Biology 9 (2), 161–185.

Steffen, W., Sanderson, A., Tyson, P.D., Jäger, J., Matson, P.A., Moore III, B., Oldfield, F., Richardson, K., Schellnhuber, H.J., Turner II, B.L., Wasson, R.J., 2004. Global Change and the Earth System. A Planet Under Pressure, Springer, Berlin.

Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature. Ambio 36 (8), 614–621.

Schwarzlmüller, E., 2009. Human appropriation of aboveground net primary production in Spain, 1955-2003: An empirical analysis of the industrialization of land use. Ecological Economics 69, 282–291 (this issue).

Turner II, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B., 1990. The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years. Cambridge University Press, Cambridge.

Turner II, B.L., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Sciences of the USA 104 (52), 20666–20671.

Tüxen, R., 1956. Die heutige potentielle natürliche Vegetation als Gegenstand der Vegetationskartierung. Angewandte Pflanzensoziologie 13, 5–42.

UN, 2000. Forest Resources of Europe, CIS, North America, Australia, Japan and New Zealand (industrialized temperate/boreal countries). UN-ECE/FAO Contribution to the Global Forest Resources Assessment, 2000. Main Report ECE/TIM/SP/17. United Nations Publications, New York, Geneva.

Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., Matson, P.A., 1986. Human Appropriation of the Products of Photosynthesis. BioScience 36 (6), 363–373.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human Domination of Earth`s Ecosystems. Science 277, 494–499.

Waide, R.B., Willig, M.R., Steiner, C.F., Mittelbach, G., Gough, L., Dodson, S.I., Juday, G.P., Parmenter, R., 1999. The Relationship Between Productivity and Species Richness. Annual Review of Ecology and Systematics 30, 257–300.

Wardle, D.A., Bardgett, R.D., Klironomos, J.N., Setala, H., van der Putten, W.H., Wall, D.H., 2004. Ecological Linkages Between Aboveground and Belowground Biota. Science 304 (5677), 1629–1633.

White, R., Murray, S., Rohweder, M., 2000. Grassland Ecosystems. Pilot analysis of global ecosystems. World Resources Institute, Washington DC.

Whittaker, R.H., Likens, G.E., 1973. Primary Production: The Biosphere and Man. Human Ecology 1 (4), 357–369.

Wright, D.H., 1983. Species-energy theorie: An extension of the species-area theory. Oikos 41, 495–506.

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

Yevich, R., Logan, J.A., 2003. An assessment of biofuel use and burning of agricultural waste in the developing world. Global Biogeochemical Cycles 17 (4), 6-1-6-40.

Zika, M., Erb, K.-H., 2009. The global loss of net primary production resulting from human-induced soil degradation in drylands. Ecological Economics 69 310-318 (this issue).