ISBN 978-94-007-1176-1

Chapter 2
Socioeconomic Metabolism and the Human Appropriation of Net Primary Production: What Promise Do They Hold for LTSER?

Helmut Haberl, Karl-Heinz Erb, Veronika Gaube, Simone Gingrich, and Simron Jit Singh

Abstract This chapter reviews approaches to analysing the 'metabolism' of socioeconomic systems consistently across space and time. Socioeconomic metabolism refers to the material, substance or energy throughput of socioeconomic systems, i.e. all the biophysical resources required for production, consumption, trade and transportation. We also introduce the broader concept of socio-ecological metabolism, which additionally considers human-induced changes in material, substance or energy flows in ecosystems. An indicator related to this broader approach is the human appropriation of net primary production (HANPP). We discuss how these approaches can be used to analyse society-nature interaction at different spatial and temporal scales, thereby representing one indispensible part of the methodological tool box of LTSER. These approaches are complimentary to other methods from the social sciences and humanities, as well as to genuinely transdisciplinary approaches. Using Austria's sociometabolic transition from agrarian to industrial society from 1830 to 2000 as an example, we demonstrate the necessity of including a comprehensive stock-flow framework in order to use the full potential of the socio-ecological metabolism approach in LTSER studies. We demonstrate how this approach can be implemented in integrated socio-ecological models that can improve understanding of changes in society-nature interrelations through time, another highly important objective of LTSER.

Keywords Human appropriation of net primary production • Socioeconomic metabolism • Material flow analysis • Carbon stock • Carbon flow

H. Haberl, Ph.D. (✉) • K-H. Erb , Ph.D. • V. Gaube, Ph.D.
S. Gingrich, Ph.D. • S.J. Singh, Ph.D.
Institute of Social Ecology Vienna (SEC), Alpen-Adria Universitaet Klagenfurt, Wien, Graz, Schottenfeldgasse 29/5, Vienna 1070, Austria
e-mail: helmut.haberl@aau.at; karlheinz.erb@aau.at; veronika.gaube@aau.at; simone.gingrich@aau.at; simron.singh@aau.at

S.J. Singh et al. (eds.), *Long Term Socio-Ecological Research*, Human-Environment Interactions 2, DOI 10.1007/978-94-007-1177-8_2,

2.1 Introduction

One of the central aims of Long-Term Socio-Ecological Research (LTSER) is to provide scientific insights within the field of global environmental change to support transitions towards sustainability (Fischer-Kowalski and Rotmans 2009; see the Introduction Chap. 1 in this volume). Changes in stocks and flows of carbon, water, nitrogen and many other compounds are crucial aspects of global environmental change. Climate change, for example, is driven by the accumulation of gases in the atmosphere that alter the energy balance of the global climate system. Changes in the concentration of such greenhouse gases (abbreviated as GHG, the most important of these being CO_2, CH_4 and N_2O) in the atmosphere resulting from human activities are very likely responsible for most of the observed growth in global mean temperature since the mid-twentieth century (IPCC 2007). Likewise, emissions of toxic substances into water bodies or the atmosphere influence ecosystems, including agro-ecosystems and forestry systems, humans as well as buildings and other valuable artefacts at regional or even global scales (Akimoto 2003).

Human-induced changes in global biogeochemical cycles also contribute to biodiversity loss, both directly and indirectly. Nitrogen enrichment has been shown to reduce species diversity in many environments (Vitousek et al. 1997). There is evidence that avian species richness is positively related to biomass stocks in ecosystems (Hatanaka et al. 2011), implying that a reduction of biomass stocks (e.g. through deforestation) would contribute to species loss. Empirical studies suggest that species richness is lower in ecosystems where human activities reduce biomass availability (Haberl et al. 2004b, 2005). There is empirical evidence that land use is the most prominent driver of biodiversity loss, followed by climate change (Sala et al. 2000).

Mitigating climate change and reducing biodiversity loss are two cornerstones of global sustainability policies, at least since the Conventions on Biological Diversity and the United Nations Framework Convention on Climate Change, both adopted at the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro. Understanding the social and economic processes that contribute to changes in global stocks and flows of materials, energy and chemical elements allow us to gain insights into the drivers of these two highly important global environmental sustainability concerns. In other words, the concept of tracing changes in socio-ecological stocks and flows of materials and energy across time and space is a central approach of LTSER. Several chapters of this volume are built upon this approach (see Fischer-Kowalski et al., Chap. 4 in this volume; Krausmann, Chap. 11 in this volume; Gingrich et al., Chap. 13 in this volume; Krausmann and Fischer-Kowalski, Chap. 15 in this volume).

In this contribution, we outline concepts and methods suitable for analysing biophysical stocks and flows, e.g. material and energy flow accounting (often referred to as MEFA, e.g. Haberl et al. 2004a), the human appropriation of net primary production (HANPP) and related approaches for analysing socioeconomic and, more broadly, socio-ecological metabolism useful for LTSER studies. Based on a case study of Austria (1830–2000), we discuss how these methods can be used to analyse and improve understanding of socio-ecological transitions (Fischer-Kowalski and Haberl 2007; see Krausmann, Chap. 11 in this volume; Gingrich et al., Chap. 13 in this volume; Krausmann and Fischer-Kowalski, Chap. 15 in this volume).

The sociometabolic approaches discussed in this chapter are complimentary to concepts and methods used and discussed in other chapters in this volume: from environmental history, biohistory, geography and social sciences, to transdisciplinary methods as well as approaches based on modelling. Links between data-based, empirical approaches to understand material and energy flows and system-dynamic modelling methods are explicitly discussed in Sect. 2.4 of this chapter.

2.2 Socioeconomic Metabolism: Material and Energy Flow Analysis (MEFA)

All human activities depend on inputs of materials and energy from the natural environment. At the very least, food is needed to keep humans alive, healthy and able to perform work. But many activities require much more than this 'basic' or 'endosomatic' metabolism (Boyden 1992; Fischer-Kowalski and Haberl 1997; Giampietro et al. 2001). Economic activities such as production, consumption, trade, transportation, and even services need buildings, infrastructures or machinery that in turn require inputs of raw materials or manufactured goods as well as inputs of energy, be it in the form of human or animal labour or as technical energy carriers such as electricity, fuels or heat. Therefore, by thermodynamic necessity, economic processes result in outputs not only in the form of products, but also as wastes and emissions (Hall et al. 2001).

The study of biophysical flows associated with socioeconomic processes has a long-standing tradition in social and human ecology, ecological anthropology, ecological economics, industrial ecology and many other interdisciplinary fields of inquiry focused on processes of society-nature interaction. As several excellent reviews are available (e.g. Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998; Martinez-Alier 1987), we will not attempt a full review here; instead we focus on the use of these concepts within LTSER.

The concept of socioeconomic metabolism (Ayres and Kneese 1969; Ayres and Simonis 1994; Boulding 1972; Fischer-Kowalski and Haberl 1997; Martinez-Alier 1987) has been developed as an approach to study the extraction of materials or energy from the environment, their conversion in production and consumption processes, and the resulting outputs to the environment. Accordingly, the unit of analysis is the socioeconomic system (or some of its components), treated as a systemic entity, in analogy to an organism or a sophisticated machine that requires material and energy inputs from the natural environment in order to carry out certain defined functions and that results in outputs as wastes and emissions. At a very basic level, one can distinguish between two sociometabolic approaches: one that aims at forging a comprehensive account of all biophysical flows needed to build up, sustain

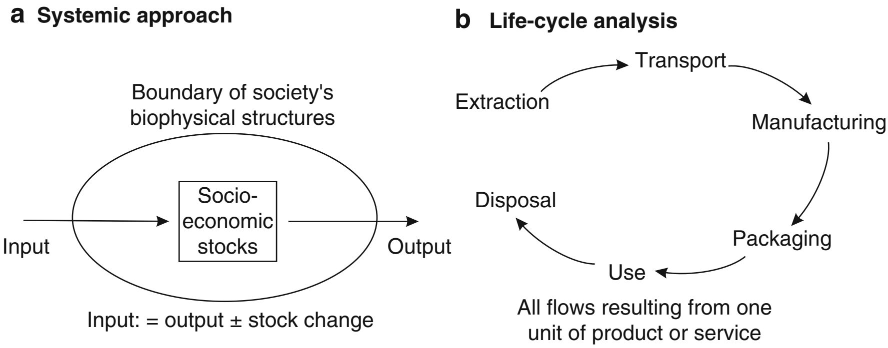

Fig. 2.1 Basic approaches to analyse socioeconomic metabolism. (**a**) Systemic approaches account for all physical flows (materials, energy, substances) required for reproduction and functioning of socioeconomic stocks. (**b**) Life-cycle analysis accounts for resource requirements or emissions from one unit of product or service throughout its entire life cycle ('cradle to grave')

and operate a defined set of socioeconomic stocks for a given reference system identified by scale (global, national, regional) or by function (household, economic sector or commercial enterprise); the other is the life-cycle analysis (LCA) approach that aims to account for resource requirements as well as wastes and emissions resulting from a single unit of product or service (Fig. 2.1).

In both cases, the essential question is how to define the system boundaries. Systemic approaches such as economy-wide material and energy flow analysis (see below) usually focus on three compartments of 'society's biophysical structures' (Fischer-Kowalski and Weisz 1999): humans, livestock (all animals kept and used by humans) and artefacts (all non-living structures constructed, maintained and used by humans, i.e. infrastructures, buildings, machinery and other durables). Human labour is the main determinant in the choice of compartments. In other words, all that is created and maintained by human labour is considered as part of society's biophysical structures or stocks.[1] Only those biophysical flows are accounted for that serve to build up, maintain or use these structures (Fischer-Kowalski 1998). While systemic metabolism approaches are used to account for and analyse metabolic flows of societies across time and space, LCA is so far mainly used for a quite different purpose, namely to optimise chains of production. Accordingly, its system boundaries are different. In LCA, the 'functional unit' may be a service such as 'movement of one person from A to B' or a defined amount and quality of a product such as 'one kilogram of fresh tomatoes' (Rebitzer et al. 2004). Although LCA might become relevant to LTSER in the future, it has not been widely used in LTSER so far, to our knowledge, and will not be further discussed here.

[1] Agricultural fields are excluded from the definition of society's biophysical stocks even though they are produced and maintained by human labour, for accounting reasons, among others. For a detailed discussion on conceptual and methodological considerations, see Fischer-Kowalski and Weisz (1999) and Eurostat (2007).

Systemic approaches to analyse socioeconomic metabolism are able to trace the flows of materials (material flow analysis or MFA), individual substances (substance flow analysis or SFA) or energy (energy flow analysis or EFA) through biophysical structures of society (humans, livestock, artefacts). MFA attempts to establish comprehensive accounts of the material throughput of a defined societal subsystem, spatially and functionally, e.g. a national economy, a city or village, a household or an economic sector. In this context, the notion of 'materials' refers to broad aggregates such as construction materials, industrial minerals and ores, biomass, fossil energy carriers or traded manufactured goods (Krausmann et al. 2009a; Weisz et al. 2006). National-level (or economy-wide) MFA takes into account all those materials used by national economies. Economy-wide MFA has meanwhile become fairly standardised and is implemented as part of national environmental statistics and book-keeping (Eurostat 2007; OECD 2008).

In contrast to the flows of broad aggregates of materials discerned in MFA, substance flow analyses (SFA) account for the flows of defined substances or even chemical elements, e.g. nitrogen (N), carbon (C) or metals such as iron (Fe), Zinc (Zn), Copper (Cu) and others (e.g., Billen et al. 2009; Erb et al. 2008; Graedel and Cao 2010; Wang et al. 2007). MFA and SFA are seen as complimentary approaches to analyse socioeconomic use of resources: While MFA provides a comprehensive picture of total resource use (with concerns over depletion of natural resources and disruption of habitats during extraction), SFA can be more easily connected to specific scarcities or environmental problems, e.g. climate change in the context of carbon flows or alteration of global biogeochemical cycles in the case of nitrogen.

In physical terms, energy is the ability to perform work. Energy is less 'tangible' and more abstract than materials (measured in kilograms, kg) or substances (measured in kg of the relevant substance, e.g. kg C in carbon flow accounts or kg N in a study on nitrogen flows). Nevertheless, scholars have long been interested in human use of energy (for an excellent review see Martinez-Alier 1987). Data on socioeconomic use of technical energy (i.e., energy flowing through artefacts) in national economies (i.e. on the country level) are readily available in conventional energy statistics and energy balances (e.g. IEA 2010). Such statistics provide indicators such as Total Primary Energy Supply (TPES) or Final Energy Use (i.e. the energy used in industry, services and households for all purposes except for the production of other energy carriers).

However, these statistics by definition exclude human consumption of food as well as feed consumption of livestock, that is, the most important energy flows of agrarian societies. Energy flow accounting (EFA) methods that fully consider biomass flows have therefore been proposed based on the same system boundaries as MFA (Haberl 2001a, b). These methods have been used to reconstruct long time-series of socioeconomic energy use on several scales, from local to national and global (Haberl 2006; Haberl et al. 2006a; Haberl and Krausmann 2007; Krausmann and Haberl 2002, 2007). EFA is therefore useful to analyse the transition from the agrarian to the industrial sociometabolic regime (Fischer-Kowalski and Haberl 2007, see below). As the changes in energy systems connected to this transition are related to many current sustainability problems, e.g. climate change, depletion of resources or biodiversity loss, they are also relevant for LTSER.

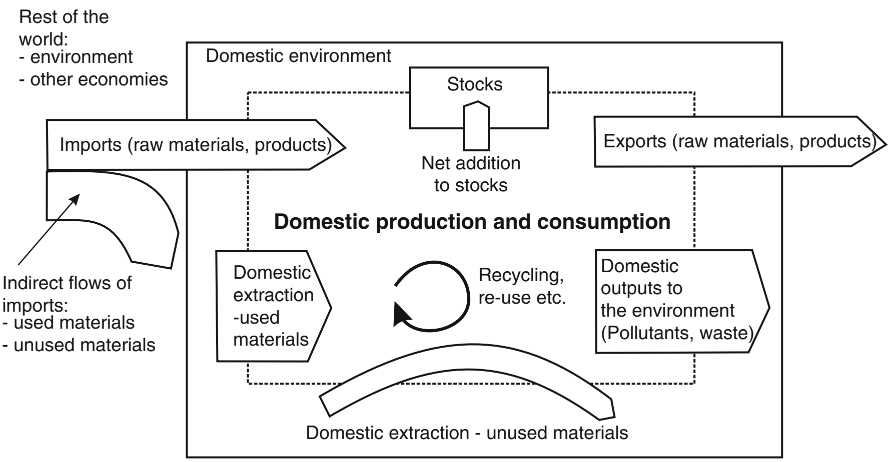

Fig. 2.2 Scheme of economy-wide (national-level) material and energy flow (MEFA) accounts (Source: Adapted from OECD 2008)

No matter whether one is interested in materials, substances or energy, it is important to note that the simple representation of socioeconomic metabolism in Fig. 2.1a becomes quite complex when applied to concrete cases. There are many reasons for this. First, at every lower scale than the global, inputs can be generated by extracting materials or energy from natural systems on one's own territory or by importing raw materials or even manufactured goods from elsewhere. The same holds for outputs which may be wastes and emissions or goods exported to other territories. Second, one needs definitions of which flows to include or exclude in the accounting system. For example, economy-wide MFA in principle includes all materials, but not air and water – except for the water contained in products.[2] MEFA accounts distinguish between those biophysical flows that directly enter the economy and those that are physically moved at an early stage of extraction and production only but are not economically useful, e.g. agricultural residues left in the field or overburden in mining (Fig. 2.2). Important indicators include the 'direct material input' (i.e. imports plus domestic extraction of used materials) and 'domestic material consumption' (i.e. direct material input minus exports) (Eurostat 2007; OECD 2008). The same indicators can be calculated for energy (Haberl 2001a). Third, the complexity of the accounts and the difficulties of avoiding double-counting increase quickly if one tries to disaggregate material or energy flow, for example to economic

[2] Water and air together comprise 85–90% of all total material input. In order not to drown other "economically valued" materials in water and air, the latter are excluded from MFA. Another reason for their exclusion is the low environmental impact of their use, a supposition which is now beginning to be questioned in the context of discussions on ecosystem services (see http://www.teebweb.org/).

sectors. Physical input-output tables have been used as a method towards that end (Hoekstra and van den Bergh 2006; Suh 2005; Weisz and Duchin 2006). Indeed, full material balances that explicitly link inputs to outputs in the manner described in Fig. 2.2 are rare. Moreover, the quantification of socioeconomic material stocks and also of the stock changes is unfortunately still in its infancy (but see Matthews et al. 2000; Kovanda et al. 2007).

Complimentary to EFA that can be used to assess the quantity and quality of energy 'metabolised' by society, analysts have long been interested in the 'energy return on investment' (abbreviated as EROI) of different energy sources used by humans (Cleveland et al. 1984; Hall et al. 1986; Odum 1971; Pimentel et al. 1973; Rappaport 1971). The EROI is defined as the ratio between the amount of energy invested by society into a process and the amount of energy gained from it:

$$\mathrm{EROI} = \frac{\text{Energy gained [J]}}{\text{Energy invested [J]}}$$

Obviously, an energy resource can only deliver a surplus of energy (a positive amount of 'net energy') if society has to invest less than it gains, i.e. if EROI is larger than 1. Under certain circumstances, societies may decide to use energy resources even at $\mathrm{EROI} < 1$, but they can do so only if possessing other energy sources with $\mathrm{EROI} > 1$ to be able to provide for these 'energetic subsidies'. For example, it has been observed that the EROI of many food products used in industrialised societies is far below 1 (Pimentel et al. 1990), but these societies can afford to subsidise these products because they have fossil fuels that have a much larger EROI at their disposal. By contrast, agrarian societies vitally depend on the EROI of agriculture being substantially larger than 1, as biomass is their most important source of net energy. Empirical analyses conducted in many places and on different spatial levels have consistently produced empirical support for this hypothesis (e.g., Pimentel et al. 1990; Krausmann 2004; Sieferle et al. 2006). Indeed, such changes in socioeconomic energy systems played a crucial role in facilitating the sociometabolic transition from agrarian to industrial society (Fischer-Kowalski and Haberl 1997, 2007; Krausmann and Haberl 2002; Haberl et al. 2011).

The above-reviewed methods to account for socioeconomic metabolism are important for sustainability science and LTSER for the following reasons (Haberl et al. 2004a): First, they provide a consistent accounting framework to assess biophysical flows associated with human activities at many levels of societal organisation, from the individual to households, towns and cities to national and supranational levels. Second, this accounting framework can be consistently applied to trace changes across historical social formations – material, substance and energy flows can be assessed for hunter-gatherers and agrarian societies as well as industrial societies, and the analyses of the changes in these biophysical flows have proven to be immensely useful in understanding differences in sustainability challenges across time and space (e.g., Dearing et al. 2007; Fischer-Kowalski and Haberl 1997, 2007; Haberl et al. 2011). Third, they provide a crucial framework to consistently link socioeconomic drivers such as decisions of actors, policies, institutions, prices or technology, to name but a few, with biophysical flows that have an obvious ecological significance, be it due to their toxicity (e.g. emissions of NO_x, SO_2, lead or dioxin), their ability to impact upon biological processes such as plant growth (e.g. reactive nitrogen) or their function as greenhouse gases (e.g., CO_2, CH_4 or N_2O).

The cumulative insights from these studies have resulted in the development of the theories of 'sociometabolic regimes' and 'sociometabolic transitions'. In the former, systematic interrelations between resource use profile, demographic trends, settlement patterns, governance structures and related environmental impacts are observed for a given mode of production. The transition from one sociometabolic regime to another, on the other hand, implies both a fundamental shift in terms of its resource use potential and environmental impacts as well as the qualitative attributes of the social system and its environmental impacts (Fischer-Kowalski and Haberl 2007; Fischer-Kowalski and Rotmans 2009; Fischer-Kowalski 2011). From an LTSER point of view, these concepts are not only useful in understanding the historical and ongoing transitions that affect global environmental change, but may also inform and aid a transition to a more sustainable future.

Accounting for socioeconomic metabolism is not sufficient, however, if one aims to understand the impact of human activities on stocks and flows of materials and energy in the biosphere. Many human activities are deliberately altering biophysical properties of ecosystems in order to increase useful output and in doing so are inducing changes in stocks and flows of materials and energy in ecosystems. The sum of these activities is denoted as land use – and is increasingly being recognised as a pervasive driver of global environmental change (Foley et al. 2005). Agriculture and forestry, but also the use of land for infrastructure and for deposition or waste absorption, almost always results in changes in stocks and flows of materials and energy in ecosystems. For example, converting natural ecosystems to cropland or managed grasslands affects not only the species composition of the ecosystem, but also water and nutrient flows, stocks and flows of carbon, water flows and retention capacity, etc. (Haberl et al. 2001; Hoekstra and Chapagain 2008; Vitousek et al. 1997). Many of these changes are associated with changes in land cover, e.g. conversions of forested land to agricultural fields, and can thus be monitored from space by remote sensing, but many other changes do not relate to such apparent alterations and are thus much more difficult to quantify, map or assess, despite their far reaching consequences for socio-ecological systems (Erb et al. 2009a; Lambin et al. 2001; Verburg et al. 2010). These processes can be analysed by using approaches to account for socio-ecological metabolism, e.g. the 'human appropriation of net primary production' (abbreviated as HANPP). Such approaches will be discussed in the following section.

2.3 Socio-ecological Metabolism: HANPP and Related Approaches

Socio-ecological metabolism (Haberl et al. 2006a) is an extension of the socioeconomic metabolism approach that aims to account for changes in both socioeconomic and ecological systems resulting from human activities. One such change particularly relevant in the LTSER context is that of biological productivity – that is, the annual net biomass production of green plants through photosynthesis (gross primary production minus plant respiration, i.e. net assimilation).

Net Primary Production (NPP) is a key parameter of ecosystem functioning (Lieth and Whittaker 1975; Lindeman 1942; Whittaker and Likens 1973). NPP determines the amount of trophic energy available for all heterotroph organisms (animals, fungi, microorganisms) in ecosystems. Many important processes such as nutrient cycling, build-up of organic material in soils or in above ground biomass stocks, vitally depend on NPP. NPP is connected to the resilience of ecosystems and to their capacity to provide services, such as biomass supply through agriculture and forestry, but also the buffering capacity or the absorption capacity for wastes and emissions (Millennium Ecosystem Assessment 2005). Human alterations of the availability of NPP in ecosystems are therefore ecologically relevant almost by definition (Gaston 2000; Kay et al. 1999; Vitousek et al. 1986; Wright 1983, 1990).

One of the indicators to measure human impact on biological productivity is the 'human appropriation of net primary production', abbreviated as HANPP. HANPP provides a framework to account for changes in biomass flows in ecosystems resulting from land use (Vitousek et al. 1986; Haberl et al. 2007a). There are two equivalent definitions of HANPP:

$$\mathrm{HANPP} := \mathrm{NPP}_0 - \mathrm{NPP}_t \tag{1}$$

$$\mathrm{HANPP} := \Delta\mathrm{NPP}_{LC} + \mathrm{NPP}_h \tag{2}$$

Definition (1) represents an ecological perspective: It defines HANPP as the change in biomass availability in ecosystems resulting from land use, i.e. as the difference between the NPP of potential natural vegetation (NPP_0) – the NPP of the vegetation assumed to exist in the absence of human interventions under current climate conditions – and the fraction of the actual vegetation NPP (abbreviated NPP_{act}) remaining in ecosystems after harvest. Harvest is denoted as NPP_h and the amount of NPP remaining in the ecosystem as NPP_t (see Fig. 2.3). Definition (2) is equivalent, but defines HANPP from a socioeconomic perspective: Land use changes the NPP of the vegetation by supplanting potential vegetation with actual vegetation – the difference between NPP_0 and NPP_{act} is denoted as ΔNPP_{LC}. In addition, harvest (NPP_h) removes NPP from the ecosystem, thereby reducing the amount of biomass remaining available in the ecosystem for all heterotrophic food chains or for biomass accumulation.

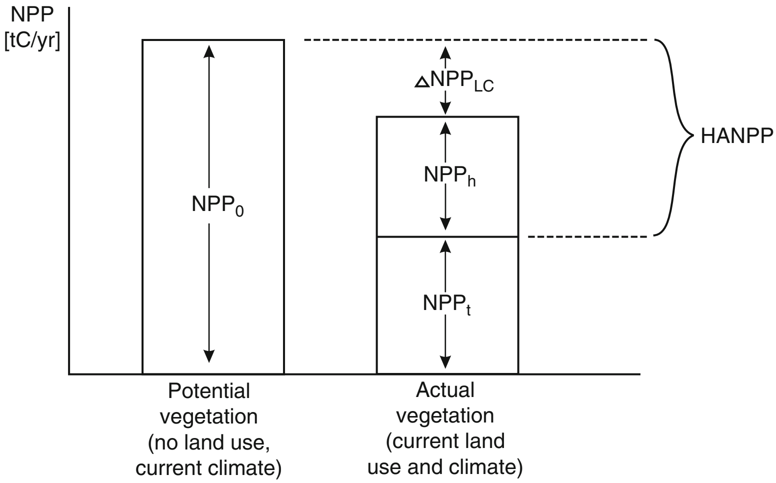

Fig. 2.3 Definition of HANPP – see text for explanation (Source: Modified after Krausmann et al. 2009b)

HANPP is related to sustainability issues such as food supply from ecosystems to society,[3] the 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 (Haberl et al. 2004b, 2005). HANPP is connected to changes in 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 fertiliser is an important factor for agricultural productivity – also N flows. HANPP is therefore directly related to global, human-induced alterations of biogeochemical cycles (Steffen et al. 2004).

Current global HANPP levels are at approximately one quarter of NPP_0 (referring to the year 2000; Haberl et al. 2007a), underpinning the notion that human activities have begun to overwhelm the great forces of nature, thereby driving the earth system into a new geological era, the 'anthropocene' (Crutzen and Steffen 2003; Steffen et al. 2007). Recent research suggests that HANPP could become a potent indicator of human pressures on biodiversity (Haberl et al. 2004b, 2005). Despite a broad acknowledgement of a strong interrelation between the NPP flow in ecosystems and biodiversity, however, there are discussions on the mathematical form of this interrelation (Waide et al. 1999; Haberl et al. 2009b). Empirical findings so far indicate

[3] For example, converting natural ecosystems to cropland increases HANPP. Increasing yields per unit area and year or reducing losses in the production chain allows the HANPP per unit of final product to be reduced and therefore HANPP to be 'decoupled' from supply of food or other land-dependent products.

that high HANPP levels do not correlate with high biodiversity levels, giving indirect evidence that HANPP can be used as an indicator for socioeconomic pressures on biodiversity (Haberl et al. 2007b).

Recent research has demonstrated that HANPP can be assessed with reasonable effort and precision at many spatial and temporal levels. Global maps of terrestrial HANPP in the year 2000 at a resolution of approximately 10 km are readily available (Haberl et al. 2007a).[4] Several long-term (decadal to centennial) country-level HANPP studies have meanwhile been conducted (e.g. Krausmann 2001; Kastner 2009; Musel 2009; Schwarzlmüller 2009, see e.g. Erb et al. 2009b).[5] Such studies have proven to be valuable in improving understanding of ecological implications of sociometabolic transitions (Fischer-Kowalski and Haberl 2007, see next section), an issue of paramount importance for LTSER. Of course, HANPP is no panacea. For example, while HANPP is a suitable indicator of overall land-use intensity, it is not well-suited to capturing cropland intensification: Intensification drives up NPP_{act} and NPP_h in parallel. In effect, even large increases in yields do not show up as an increase in HANPP. Additional indicators such as nutrient balances and EROI are required to make such effects visible (Erb et al. 2009b).

The HANPP framework can be extended in at least two directions that are relevant in LTSER. First, in addition to the HANPP on a defined territory, one can also calculate the HANPP caused by, or 'embodied in', the products consumed by a population. This is captured by the concept of 'embodied HANPP', abbreviated as eHANPP (Erb et al. 2009c; Haberl et al. 2009a). The eHANPP concept is related to approaches such as 'virtual water' (Allan 1998) and the 'water footprint' (Hoekstra and Chapagain 2007; Gerbens-Leenes et al. 2009). Embodied HANPP is the HANPP resulting from the consumption of all products used by a population. National eHANPP can be calculated by adding to the HANPP on a country's own territory the HANPP resulting from imports and subtracting the HANPP resulting from exports (Erb et al. 2009c; Haberl et al. 2009a).

Let us consider the example of Australia: This highly industrialised, but sparsely populated country (two inhabitants per square kilometre) has an HANPP on its national territory of 708 million tonnes of dry-matter biomass (Mt/year), but the eHANPP related to the consumption of its population is only 177 Mt/year. In other words, net biomass trade results in a 'net export' of three-quarters of Australia's HANPP. By contrast, Japan, with its high population density (330 inhabitants per square kilometre) has an HANPP on its own territory of 113 Mt/year, but the eHANPP related to its consumption is more than five times higher and amounts to 581 Mt/year – hence, Japan obviously could not generate sufficient supplies on its

[4] Gridded HANPP data can be freely downloaded at http://www.uni-klu.ac.at/socec/inhalt/1191.htm

[5] HANPP studies are not restricted to terrestrial ecosystems, but can also be used to analyse trends, trajectories and the magnitude of human impacts on e.g. marine ecosystems (Pauly et al. 2005; Swartz et al. 2010). The utility of these approaches in LTSER has so far not been explored.

own territories, at least at its current consumption levels. Such data allow us to analyse the 'teleconnections' between cities and their hinterlands or between exporting and importing countries (Haberl et al. 2009a).

The eHANPP concept thus allows us to explicitly analyse the impacts of consumption on terrestrial systems in terms of their trophic energy flows. Second, one can also link the flows accounted for in HANPP assessments to stocks of biomass and carbon in biota and soils (Erb 2004; Erb et al. 2008; Haberl et al. 2001; Gingrich et al. 2007; see next section). This is particularly relevant as it allows us to establish full carbon balances thus providing a comprehensive picture of the carbon stocks and flows in a defined country or region that considers not only C-flows resulting from socioeconomic metabolism but also those resulting from land-use change.

Approaches that are conceptually related to HANPP can be developed for other relevant resources as well. For example, one can calculate the 'human appropriation of freshwater' (Postel et al. 1996; Weiß et al. 2009) and human-induced changes in river runoff (Vörösmarty et al. 1997). Another related concept is the mapping of the relation between human-induced and natural metal flows (Rauch and Pacyna 2009; Rauch 2010).

2.4 Austria 1830–2000: Towards a System-Dynamic Model of Carbon Stocks and Flows

In this section we summarise recent research on the stocks and flows of carbon in Austria from 1830 to 2000 and propose how this transition might be analysed using a system-dynamic model. The analysis of changes in carbon stocks and flows in Austria through almost two centuries provides an example of how the above-discussed methods and approaches can help to integrate empirical, data-driven and analytic, system-dynamic approaches for LTSER. Integrating system-dynamic modelling with data generation and interpretation allows us to test hypotheses on the relative importance of drivers and on interrelations between important factors and is therefore an important approach in LTSER (van der Leeuw 2004).

We focus in this example on carbon, not only because these data are available from previous research (Erb 2004; Erb et al. 2007, 2008; Gingrich et al. 2007) but also because changes in stocks and flows of carbon have an immediate bearing upon many contemporary sustainability challenges. Carbon is an essential chemical element indispensable not only for all living organisms (about half of dry-matter biomass is carbon), but also a major constituent of many materials, most prominently fossil fuels. Its concentration in the atmosphere is a major determinant of the earth's climate system because CO_2 absorbs infrared radiation and can thereby alter the earth's radiation balance. Carbon is therefore highly important for socioeconomic and ecological systems alike.

During the period 1830–2000, Austria underwent an almost complete sociometabolic transition from an agrarian to an industrial society. Population grew by a factor of 2.3 from 3.6 to 8.1 million. The agrarian share of the population (i.e. farmers and their families) dropped from 75 to 5%. The contribution of agriculture to GDP even declined to 1.4% in the year 2000, while total GDP rose by a factor of 28 and per-capita GDP by a factor of 12 (Krausmann and Haberl 2007).

At the beginning of the period in question, Austria was still a predominantly agrarian country.[6] In 1830, biomass accounted for 99% of the socioeconomic energy input for food, feed and fibre but also for mechanical work, light and heat. Hydropower was used by water mills that were important for processes such as grain milling or metal works, but the amount of energy gained through this process was below 1% of total socioeconomic energy input. Similarly, some coal was already used at that time, but the amount was almost negligible compared to biomass.

The first phase of Austria's industrialisation until World War I was largely powered by coal. At that time, the abundant coal reserves of Bohemia and southern Poland were 'domestic' resources: Although the coal had to be 'imported' to the current Austrian territory, the coal in fact came from other parts of the same country; that is, the Austro-Hungarian monarchy. This changed abruptly with World War I, after which most coal had to be imported from what were now independent countries. This in effect resulted in a restructuring of the Austrian industry, with less emphasis on heavy industry after the war and lower levels of coal use. After World War II, Austria's rapid economic growth was mostly powered by oil products, later by natural gas and by a considerable hydropower programme that led to the utilisation of about three-quarters of the economically usable potential, continuing into the present day (for detail see Krausmann and Haberl 2002, 2007).

All of this resulted in major changes in Austria's socioeconomic carbon flows. In 1830, almost all of the carbon metabolised by Austrian society came from biomass harvested on Austria's own territory through either agriculture or forestry (coal was insignificant at that point in time, contributing less than 1% to Austria's total energetic metabolism). By contrast, in the year 2000, fossil fuels played a major role, although the carbon contained in biomass was still by no means negligible (Fig. 2.4a). Almost all the carbon metabolised by the Austrian economy flowed to the atmosphere, mostly as CO_2, but at the same time plant growth also removed CO_2 from the atmosphere through photosynthesis. Carbon from biomass is often exempted on these grounds from greenhouse gas accounts, but the general assumption that the release of carbon in biomass to the atmosphere would be 'carbon neutral' because it is balanced by plant growth has long been recognised as being imprecise (Schlamadinger et al. 1997). In fact, this assumption may even result in major flaws, in particular in cases where large stock changes are triggered, such as with the conversion of pristine forests to used forests or to agricultural fields – a recent recognition that mandates revision of GHG accounting rules (Searchinger et al. 2009).

[6] Note that before 1918 the current territory of Austria was part of the much larger Austro-Hungarian monarchy. For this period, we were obliged to use data that refer to a territory that is similar, but not exactly identical to Austria's current territory. These data were used to extrapolate to Austria in its current boundaries, in order to generate a consistent time series (see Krausmann and Haberl 2007 for detail).

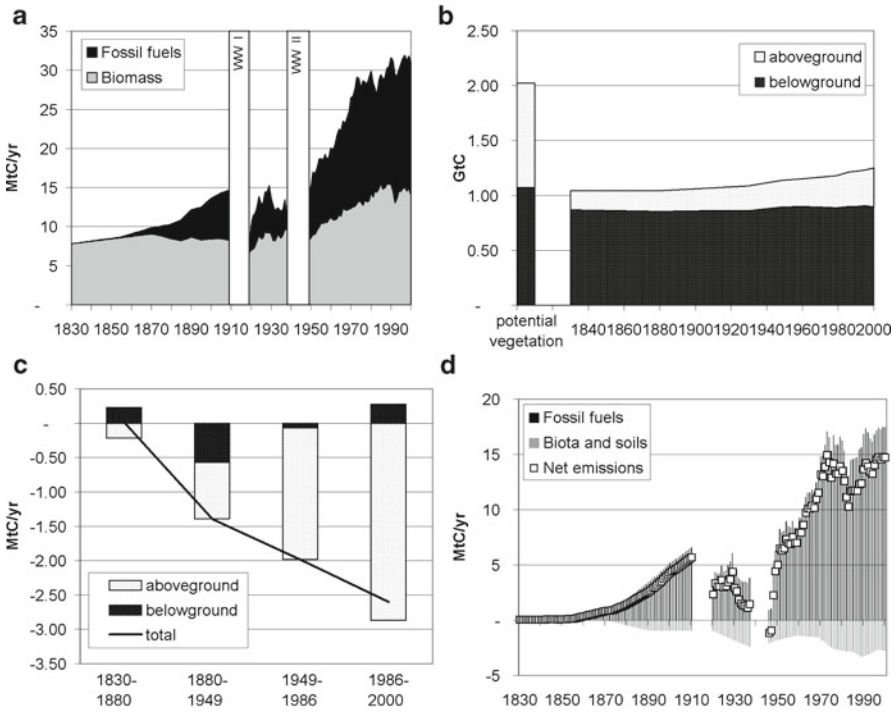

Fig. 2.4 Stocks and flows of carbon in Austria 1830–2000. (**a**) Socioeconomic carbon flows per year. (**b**) Carbon stocks in biota and soils in billion tonnes of carbon. (**c**) Net carbon exchange between atmosphere and biota/soils. (**d**) Net carbon emissions considering the terrestrial carbon sink (Source: Redrawn after Erb et al. 2008; Gingrich et al. 2007)

Correct treatment of this critical issue requires a clear distinction between stocks and flows (Körner 2009). Most of the carbon absorbed by green plants during photosynthesis is metabolised either by plants or by heterotrophic organisms and therefore released back to the atmosphere. Compared to these yearly flows, net changes in stocks – either in the soil, e.g. as soil organic carbon (SOC), or above-ground in the carbon content of standing biomass stocks ('standing crop') – are comparably small. Estimating the net release ('source') or net absorption ('sink') of carbon therefore requires the assessment of carbon stocks in biota and soils at different points in time. If the stock is growing, one can assume that biota and soils have acted as a carbon sink, while in the opposite case they have acted as a source, i.e. emitted carbon to the atmosphere.

In Austria, carbon stocks in biota and soils are substantially lower than they would be in the absence of human use of the land (Fig. 2.4b). The reason is that most of Austria's area would be forested if not used by humans, whereas a considerable proportion of these natural forests have been replaced by agro-ecosystems (cropland, grasslands) by humans mainly from the Middle Ages onwards (in addition, natural forests have been almost entirely replaced by managed forests). As shown in

Fig. 2.4b, carbon stocks in biota and soils have been steadily increasing since 1880, thereby resulting in a considerable net uptake of carbon: While biota and soils were almost balanced from 1830 to 1880, the net carbon uptake increased to approximately 2.9 million tC per year in the period 1996–2000 (Fig. 2.4c). The reason for this phenomenon – which is typical for many industrial economies and is known as 'forest transition' (Mather and Fairbairn 1990; Kauppi et al. 2006; Meyfroidt et al. 2010) – is that cropland and grassland areas are shrinking and forests are growing both in terms of area and in terms of stocking density, i.e. in carbon stocks per unit area (Erb et al. 2008; Gingrich et al. 2007). In Austria, forest area grew by more than one-fifth in the last 170 years. In that period, infrastructure areas grew by a factor of four, while cropland area was reduced by one-third and pastures and meadows by one-fifth (Krausmann 2001).

That biota and soils in Austria absorb more carbon than they release can, at least in a first-order approach, be interpreted as justification for assuming that carbon releases through biomass combustion to the atmosphere were indeed 'carbon neutral'. In fact, Austrian ecosystems not only produced all that biomass, they even sequestered carbon at the same time. However, there are some caveats. First, this view neglects the possibility that Austria's biomass consumption causes carbon releases elsewhere. The analysis of this issue is still in its infancy, and considering such flows might well influence the overall balance (Gavrilova et al. 2010; Kastner et al. 2011). Second, it would also be necessary to consider the counterfactual. For example, if wood harvest in Austrian forests were to be reduced, the forests would sequester considerably more carbon. This effect is substantial and might well cancel out any emission reduction if additional wood were to be harvested in order to burn it instead of fossil fuels (Haberl et al. 2003).

The most important caveat, however, is the following one: The reduction in farmland was made possible by massive technological change in agriculture that helped to increase yields and conversion efficiencies in the livestock sector (e.g. feed to meat ratios) by large margins. These changes were massive enough to allow for surges in agricultural yields and a 70% increase in primary biomass harvests on the Austrian territory from 1830 to 2000, without increasing HANPP. In fact, an empirical analysis suggests that aboveground HANPP fell by some 15–20% over this period. This was so largely because, due to agricultural intensification, NPP_{act} increased more than NPP_h, and because the fraction of NPP_h that could be used as commercial product increased by large margins as well (Krausmann 2001). These technological improvements were only possible due to large-scale inputs of fossil fuels in agriculture, both directly (e.g. tractors) and indirectly (e.g. artificial N fertiliser). These changes have resulted in a massive reduction of the EROI of agriculture from around 6:1 in 1830 to approximately 1:1 in the year 2000 (Krausmann 2004). Ironically, the very same input of fossil fuels that resulted in the massive increases in total GHG emissions also helped to turn Austria's biota and soils into a carbon sink. It is therefore fully justified to speak of a 'fossil-fuel powered carbon sink' (Erb et al. 2007).

Similar trajectories of forest cover and carbon stocks are described for many countries (e.g., Kauppi et al. 2006; Kuemmerle et al. 2011), which suggests that such complex interrelations and feedback loops between land intensification, forest

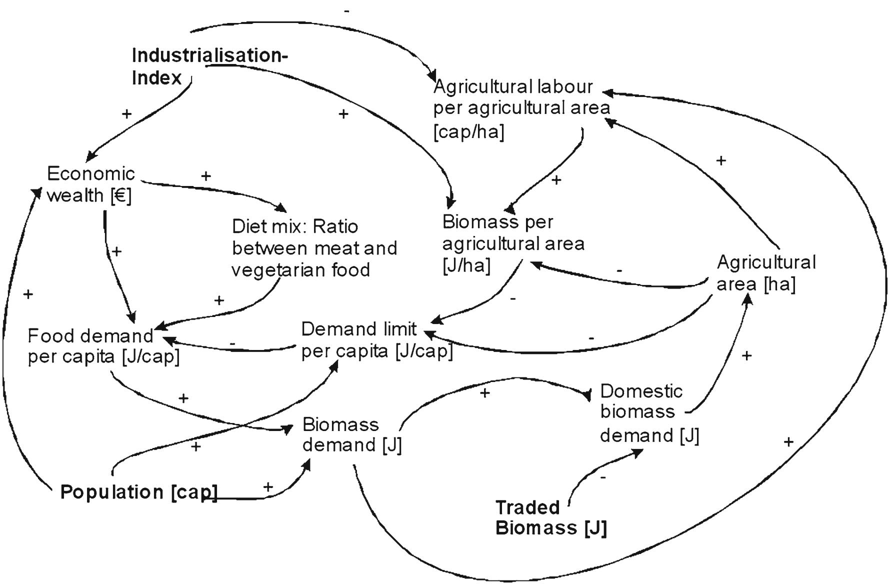

Fig. 2.5 Preliminary causal loop model of the land use model for Austria 1830–2000 – see text for explanation (Source: authors' own figure)

growth, and the overall socioeconomic energy system are ubiquitous. Our understanding of the spatial and temporal interrelation of these feedback loops, however, is still limited, as many parameter and causal chains show time lags and are subject to trajectories that operate at other spatial scales, e.g. mega-trends such as the globalisation of production and consumption.

The development of algorithmic system-dynamic models has a high potential to advance our current understanding of the complex mechanisms underlying land-use change during socio-ecological transitions from agrarian to industrial society. System-dynamic models have been found to be useful heuristic tools that allow advances in the causal understanding of complex system change: they entail a well-considered reductionism, pragmatism and a clarity of definitions and assumptions at the same time (van der Leeuw 2004). Simple algorithmic formulation of the causal relationships and feedback loops between the highly interlinked factors can be implemented in readily available system-dynamic modelling software.[7]

System-dynamic modelling requires a definition of a so-called causal diagram which serves as the basis of technical implementation of mathematically described interrelations between system components. This might already deliver crucial insights, because causal diagrams depict all key elements of the system under study and require the explicit definition of the relationships between them (Garcia 2006). An example of such a diagram is displayed in Fig. 2.5. Once the variables

[7] Free software is readily available, for example Vensim, http://www.vensim.com/

of the system are defined the hypothetical relationships can be represented as arrows between them (Fig. 2.5), indicating directions of causal interdependencies. Each arrow is marked with a plus (+) or minus (−) sign that indicates if a change in the influencing variable will produce a change of the same direction in the target variable or if the effect will be the opposite. Such causal simulation models are capable of reconstructing the trajectory of human-driven land-use change (Lambin et al. 2000; Verburg et al. 2000).

In the model scheme displayed in Fig. 2.5, the four major socioeconomic factors that influence patterns and dynamics of land use are: (1) population, including changes over time, (2) changes in food consumption, (3) technological change, especially in agriculture, and (4) changes in international trade. Biomass harvest is directly influenced by national biomass demand and supply, moderated by trade. Biomass demand is a function of population and the consumption pattern of the population – e.g. diet behaviour. Biomass supply depends not only on natural conditions, but also on the dynamic interplay of labour, capital, livestock and land. External factors and dynamics as input variables used in the model could be (1) Industrialisation-Index indicating the technological change, (2) population numbers and (3) the traded biomass (all of these are highlighted in bold letters in Fig. 2.5), but different notions would also be valid (e.g. population numbers as an endogenous variable). Such causal models can be tested against historical statistics on land-use change, socioeconomic metabolism and land-cover change and are suitable heuristic tools for advancing our understanding of long-term socio-ecological changes (Haberl et al. 2006b; Turner et al. 2007).

2.5 Outlook

The study of global environmental change requires a long-term scientific perspective of society-nature interactions. Careful conceptual and methodological considerations are crucial in outlining a scientific agenda for this emerging field of LTSER. In this contribution, we have tried to show the analytical power of socioeconomic and socio-ecological metabolism approaches for understanding local, regional and global environmental changes. These approaches provide tools to assess and monitor socio-ecological interactions and provide insights into the cumulative effects of human activities and their sustainability challenges from a cross-scalar perspective.

Gauging from historical examples of various social formations and modes of production, it becomes evident that the study of the systemic interrelations between biophysical and socio-cultural attributes is key (Fischer-Kowalski and Haberl 2007): Insights into these dynamics are of high relevance for a sustainability science agenda within LTSER, not only in terms of mapping biophysical flows, but also in understanding feedback loops between these and other social, cultural, economic and political variables (Haberl et al. 2006b). This research gap will hopefully be a major focus of future LTSER. The sociometabolic approaches discussed in this chapter thus have to be seen as complimentary to other approaches, e.g. those from social sciences and humanities, and as representing an important part of the methodological toolbox of LTSER. In our view, the research discussed in this chapter shows that LTSER is maturing, developing and extending methods and has the potential to synthesise such methods and approaches in analysing and interpreting long-term changes.

Long-term socio-ecological research requires interdisciplinary efforts, dealing as it does with a plethora of paradigms and methods that require us to bring together not only the social and natural sciences, but also civil society and policy makers as major stakeholders to be considered. This chapter offers promising perspectives in dealing with some of the conceptual and methodological challenges in LTSER. Thus far, however, research is still biased towards understanding the biophysical aspects of society-nature interactions. Notwithstanding, there is an urgent need for more social science input, integrative and transdisciplinary research, as well as the establishment of effective communication pathways between scientists and other stakeholders, including the political system, to be able to influence policy and human behaviour effectively with respect to the choices we make. Global sustainability depends upon moving beyond purely ecological considerations only and towards a system that presupposes the equitable distribution of resources, both in quantitative and qualitative terms, for the current as well as for future generations.

Acknowledgments This chapter has profited from research funded by the Austrian Science Fund (FWF), project P20812-G11, by the Austrian Ministry of Science within the research programme proVISION, and from the FP7 Project Volante. It contributes to the Global Land Project (http://www.globallandproject.org) and to long-term socio-ecological research (LTSER) initiatives within LTER Europe (http://www.lter-europe.ceh.ac.uk/).

References

Akimoto, H. (2003). Global air quality and pollution. *Science, 302*, 1716–1719.

Allan, J. A. (1998). Virtual water: A strategic resource. Global solutions to regional deficits. *Ground Water, 36*, 545–546.

Ayres, R. U., & Kneese, A. V. (1969). Production, consumption and externalities. *The American Economic Review, 59*, 282–297.

Ayres, R. U., & Simonis, U. E. (Eds.). (1994). *Industrial metabolism: Restructuring for sustainable development*. Tokyo/New York/Paris: United Nations University Press.

Billen, G., Barles, S., Garnier, J., Rouillard, J., & Benoit, P. (2009). The food-print of Paris: Long-term reconstruction of the nitrogen flows imported into the city from its rural hinterland. *Regional Environmental Change, 9*, 13–24.

Boulding, K. E. (1972). The economics of the coming spaceship Earth. In H. E. Daly (Ed.), *Steady state economics* (pp. 121–132). San Francisco: W.H. Freeman.

Boyden, S. V. (Ed.). (1992). *Biohistory: The interplay between human society and the biosphere – Past and present*. Paris/Casterton Hall/Park Ridge: UNESCO and Parthenon Publishing Group.

Cleveland, C. J., Costanza, R., Hall, C. A. S., Kaufmann, R. K., & Stern, D. I. (1984). Energy and the U.S. economy: A biophysical perspective. *Science, 225*, 890–897.

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

Dearing, J. A., Graumlich, L. J., Grove, R., Grübler, A., Haberl, H., Hole, F., Pfister, C., & van der Leeuw, S. E. (2007). Integrating socio-environment interactions over centennial timescales: Needs and issues. In R. Costanza, L. J. Graumlich, & W. Steffen (Eds.), *Sustainability or collapse? An integrated history and future of people on Earth* (pp. 243–274). Cambridge, MA/London: The MIT Press.

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*, 803–815.

Erb, K.-H. (2004). Land-use related changes in aboveground carbon stocks of Austria's terrestrial ecosystems. *Ecosystems, 7*, 563–572.

Erb, K.-H., Haberl, H., & Krausmann, F. (2007). The fossil-fuel powered carbon sink. Carbon flows and Austria's energetic metabolism in a long-term perspective. In M. Fischer-Kowalski & H. Haberl (Eds.), *Socioecological transitions and global change: Trajectories of social metabolism and land use* (pp. 60–82). Cheltenham/Northampton: Edward Elgar.

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

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

Erb, K.-H., Krausmann, F., & Haberl, H. (Eds.) (2009b). *Analyzing the global human appropriation of net primary production – Processes, trajectories, implications* (Special section of Ecological Economics 69(2)). Amsterdam: Elsevier.

Erb, K.-H., Krausmann, F., Lucht, W., & Haberl, H. (2009c). Embodied HANPP: Mapping the spatial disconnect between global biomass production and consumption. *Ecological Economics, 69*, 328–334.

Eurostat (Ed.). (2007). *Economy-wide material flow accounting. A compilation guide*. Luxembourg: European Statistical Office.

FAO. (2004). *FAOSTAT 2004, FAO statistical databases: Agriculture, fisheries, forestry, nutrition*. Rome: FAO.

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

Fischer-Kowalski, M. (2011). Analyzing sustainability transitions as a shift between socio-metabolic regimes. *Environmental Innovation and Societal Transitions, 1*, 152–159.

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

Fischer-Kowalski, M., & Haberl, H. (Eds.). (2007). *Socioecological transitions and global change: Trajectories of social metabolism and land use*. Cheltenham/Northhampton: Edward Elgar.

Fischer-Kowalski, M., & Hüttler, W. (1998). Society's Metabolism. The intellectual history of material flow analysis, part II: 1970–1998. *Journal of Industrial Ecology, 2*, 107–137.

Fischer-Kowalski, M., & Rotmans, J. (2009). Conceptualizing, observing and influencing social-ecological transitions. *Ecology and Society, 14*, 3. (Online) URL: http://www.ecologyandsociety.org/vol4/iss2/art3

Fischer-Kowalski, M., & Weisz, H. (1999). Society as a hybrid between material and symbolic realms. Toward a theoretical framework of society-nature interaction. *Advances in Human Ecology, 8*, 215–251.

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

Garcia, J. M. (Ed.). (2006). *Theory and practical exercises of system dynamics*. Barcelona: Juan Martin Garcia.

Gaston, K. J. (2000). Global patterns in biodiversity. *Nature, 405*, 220–227.
Gavrilova, O., Jonas, M., Erb, K.-H., & Haberl, H. (2010). International trade and Austria's livestock system: Direct and hidden carbon emission flows associated with production and consumption of products. *Ecological Economics, 69*, 920–929.
Gerbens-Leenes, W., Hoekstra, A. Y., & van der Meer, T. H. (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences, 106*, 10219–10223.
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*, 334–338.
Giampietro, M., Mayumi, K., & Bukkens, S. G. F. (2001). Multiple-scale integrated assessment of societal metabolism: An analytical tool to study development and sustainability. *Environment, Development and Sustainability, 3*, 275–307.
Gingrich, S., Erb, K.-H., Krausmann, F., Gaube, V., & Haberl, H. (2007). Long-term dynamics of terrestrial carbon stocks in Austria. A comprehensive assessment of the time period from 1830 to 2000. *Regional Environmental Change, 7*, 37–47.
Graedel, T. E., & Cao, J. (2010). Metal spectra as indicators of development. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 20905–20910.
Haberl, H. (2001a). The energetic metabolism of societies, part I: Accounting concepts. *Journal of Industrial Ecology, 5*, 11–33.
Haberl, H. (2001b). The energetic metabolism of societies, part II: Empirical examples. *Journal of Industrial Ecology, 5*, 71–88.
Haberl, H. (2006). The global socioeconomic energetic metabolism as a sustainability problem. *Energy – The International Journal, 31*, 87–99.
Haberl, H., & Krausmann, F. (2007). The local base of the historical agrarian-industrial transition, and the interaction between scales. In M. Fischer-Kowalski & H. Haberl (Eds.), *Socioecological transitions and global change: Trajectories of social metabolism and land use* (pp. 116–138). Cheltenham/Northampton: Edward Elgar.
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*, 929–942.
Haberl, H., Erb, K.-H., Krausmann, F., Adensam, H., & Schulz, N. B. (2003). Land-use change and socioeconomic metabolism in Austria. Part II: Land-use scenarios for 2020. *Land Use Policy, 20*, 21–39.
Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H., & Winiwarter, V. (2004a). Progress Towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy, 21*, 199–213.
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. (2004b). Human appropriation of net primary production and species diversity in agricultural landscapes. *Agriculture, Ecosystems and Environment, 102*, 213–218.
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 and Environment, 110*, 119–131.
Haberl, H., Weisz, H., Amann, C., Bondeau, A., Eisenmenger, N., Erb, K.-H., Fischer-Kowalski, M., & Krausmann, F. (2006a). The energetic metabolism of the European Union and the United States: Decadal energy input time-series with an emphasis on biomass. *Journal of Industrial Ecology, 10*, 151–171.
Haberl, H., Winiwarter, V., Andersson, K., Ayres, R. U., Boone, C. G., Castillio, A., Cunfer, G., Fischer-Kowalski, M., Freudenburg, W. R., Furman, E., Kaufmann, R., Krausmann, F., Langthaler, E., Lotze-Campen, H., Mirtl, M., Redman, C. A., Reenberg, A., Wardell, A. D., Warr, B., & Zechmeister, H. (2006b). From LTER to LTSER: Conceptualizing the socio-economic dimension of long-term socio-ecological research. *Ecology and Society*, *11,* 13. (Online), http://www.ecologyandsociety.org/vol11/iss2/art13/

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

Haberl, H., Erb, K.-H., Plutzar, C., Fischer-Kowalski, M., Krausmann, F., Hak, T., Moldan, B., & Dahl, A. L. (2007b). Human appropriation of net primary production (HANPP) as indicator for pressures on biodiversity. In *Sustainability indicators. A scientific assessment* (pp. 271–288). Washington, DC, Covelo/London: SCOPE, Island Press.

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

Haberl, H., Gaube, V., Díaz-Delgado, R., Krauze, K., Neuner, A., Peterseil, J., Plutzar, C., Singh, S. J., & Vadineanu, A. (2009b). 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*, 1797–1812.

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Martinez-Alier, J., & Winiwarter, V. (2011). A socio-metabolic transition towards sustainability? Challenges for another great transformation. *Sustainable Development, 19*, 1–14.

Hall, C. A. S., Cleveland, C. J., & Kaufmann, R. K. (Eds.). (1986). *Energy and resource quality. The ecology of the economic process*. New York: Wiley-Interscience.

Hall, C. A. S., Lindenberger, D., Kümmel, R., Kroeger, T., & Eichhorn, W. (2001). The need to reintegrate the natural sciences into economics. *BioScience, 51*, 663–673.

Hatanaka, N., Wright, W., Loyin, R. H., & MacNally, R. (2011). 'Ecologically complex carbon' – Linking biodiversity values, carbon storage and habitat structure in some austral temperate forests. *Global Ecology and Biogeography, 20*, 260–271.

Hoekstra, A. Y., & Chapagain, A. K. (2007). Water footprints of nations: Water use by people as a function of their consumption pattern. *Water and Resource Management, 21*, 35–48.

Hoekstra, A. Y., & Chapagain, A. K. (Eds.). (2008). *Globalization of water. Sharing the planet's freshwater resources*. Malden: Blackwell Publishing.

Hoekstra, R., & van den Bergh, J. C. J. M. (2006). Constructing physical input-output tables for environmental modeling and accounting: Framework and illustrations. *Ecological Economics, 59*(3), 375–393.

IEA. (2010, December 19). "World energy statistics", IEA World energy statistics and balances (database). doi: 10.1787/data-00510-en. OECD Library (Klagenfurt University). International Energy Agency (IEA).

IPCC. (2007). *Climate change 2007. Synthesis report. Contribution of Working Groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge/New York: Cambridge University Press.

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.

Kastner, T., Kastner, M., & Nonhebel, S. (2011). Tracing distant environmental impacts of agricultural products from a consumer perspective. *Ecological Economics, 70*, 1032–1040.

Kauppi, P. E., Ausubel, J. H., Fang, J., Mather, A. S., Sedjo, R. A., & Waggoner, P. E. (2006). Returning forests analyzed with the forest identity. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 17574–17579.

Kay, J. J., Regier, H. A., Boyle, M., & Francis, G. (1999). An ecosystem approach for sustainability: Addressing the challenge of complexity. *Futures, 31*, 721–742.

Körner, C. (2009). Biologische Kohlenstoffsenken: Umsatz und Kapital nicht verwechseln! *Gaia, 18*, 288–293.

Kovanda, J., Havranek, M., & Hak, T. (2007). Calculation of the "Net additions to stock" indicator for the Czech Republic using a direct method. *Journal of Industrial Ecology, 11*, 140–154.

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*, 17–26.

Krausmann, F. (2004). Milk, manure and muscular power. Livestock and the industrialization of agriculture. *Human Ecology, 32*, 735–773.

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*, 177–201.

Krausmann, F., & Haberl, H. (2007). Land-use change and socio-economic metabolism. A macro view of Austria 1830–2000. In M. Fischer-Kowalski & H. Haberl (Eds.), *Socioecological transitions and global change: Trajectories of social metabolism and land use* (pp. 31–59). Cheltenham/Northampton: Edward Elgar.

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

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

Kuemmerle, T., Olofsson, P., Chaskovskyy, O., Baumann, M., Ostapowicz, K., Woodcock, C. E., Houghton, R. A., Hostert, P., Keeton, W. S., & Radeloff, V. C. (2011). Post-Soviet farmland abandonment, forest recovery, and carbon sequestration in western Ukraine. *Global Change Biology, 17*, 1335–1349.

Lambin, E. F., & Geist, H. J. (Eds.). (2006). *Land-use and land-cover change. Local processes and global impacts*. Berlin: Springer.

Lambin, E. F., Rounsevell, M. D. A., & Geist, H. J. (2000). Are agricultural land-use models able to predict changes in land-use intensity? *Agriculture, Ecosystems and Environment, 82*, 321–331.

Lambin, E. F., Turner, B. L. I., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, J. W., Coomes, O. T., Dirzo, R., Fischer, G., Folke, C., George, P. S., Homewood, K., Imbernon, J., Leemans, R., Li, X., Moran, E. F., Mortimore, M., Ramakrishnan, P. S., Richards, J. F., Skanes, H., Steffen, W., Stone, G. D., Svedin, U., Veldkamp, T. A., Vogel, C., & Xu, J. (2001). The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change, 11*, 261–269.

Lieth, H., & Whittaker, R. H. (Eds.). (1975). *Primary productivity of the biosphere*. Berlin/Heidelberg/New York: Springer.

Lindeman, R. L. (1942). The trophic-dynamic aspect of ecology. *Ecology, 23*, 399–417.

Martinez-Alier, J. (Ed.). (1987). *Ecological economics. Energy, environment and society*. Oxford: Blackwell.

Mather, A. S., & Fairbairn, J. (1990). From floods to reforestation: The forest transition in Switzerland. *The American Historical Review, 95*, 693–714.

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. (Eds.). (2000). *The weight of nations: Material outflows from industrial economies*. Washington, DC: World Resources Institute.

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, B., III, 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 CO_2, climate and land-use effects with four process-based ecosystem models. *Global Biogeochemical Cycles, 15*, 183–206.

Meyfroidt, P., Rudel, T. K., & Lambin, E. F. (2010). Forest transitions, trade, and the global displacement of land use. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 20917–20922.

Millennium Ecosystem Assessment (Ed.). (2005). *Ecosystems and human well-being – Our human planet. Summary for decision makers*. Washington, DC: Island Press.

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.

Odum, H. T. (Ed.). (1971). *Environment, power, and society*. New York: Wiley-Interscience.

OECD. (2008). *Measuring material flows and resource productivity. Synthesis report*. Paris: Organisation for Economic Co-operation and Development (OECD).

Pauly, D., Watson, R., & Alder, J. (2005). Global trends in world fisheries: Impacts on marine ecosystems and food security. *Philosophical Transactions: Biological Sciences, 360*, 5–12.

Pimentel, D., Hurd, L. E., Bellotti, A. C., Forster, M. J., Oka, I. N., Sholes, O. D., & Whitman, R. J. (1973). Food production and the energy crisis. *Science, 182*, 443–449.

Pimentel, D., Dazhong, W., & Giampietro, M. (1990). Technological changes in energy use in U.S. agricultural production. In S. R. Gliessman (Ed.), *Agroecology, researching the ecological basis for sustainable agriculture* (pp. 305–321). New York: Springer.

Postel, S. L., Daily, G. C., & Ehrlich, P. R. (1996). Human appropriation of renewable fresh water. *Science, 271*, 785–788.

Rappaport, R. A. (1971). The flow of energy in an agricultural society. *Scientific American, 225*, 117–133.

Rauch, J. N. (2010). Global spatial indexing of the human impact on Al, Cu, Fe, and Zn mobilization. *Environmental Science and Technology, 44*, 5728–5734.

Rauch, J. N., & Pacyna, J. M. (2009). Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles. *Global Biogeochemical Cycles, 23*, GB2001. doi:10.1029/2008GB003376.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B. P., & Pennington, D. W. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International, 30*, 701–720.

Sala, O. E., Chapin, F. S., III, Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sannwald, E., Huennecke, L. F., Jackson, R. B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B., Walker, M., & Wall, D. H. (2000). Global biodiversity scenarios for the year 2100. *Science, 287*, 1770–1774.

Schlamadinger, B., Apps, M. J., Bohlin, F., Gustavsson, L., Jungmeier, G., Marland, K., Pingoud, K., & Savolainen, I. (1997). Towards a standard methodology for greenhouse gas balances of bioenergy systems and comparison with fossil energy systems. *Biomass and Bioenergy, 13*, 359–375.

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.

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., Likens, G. E., Lubowski, R. N., Obersteiner, M., Oppenheimer, M., Philip Robertson, G., Schlesinger, W. H., & vid Tilman, G. (2009). Fixing a critical climate accounting error. *Science, 326*, 527–528.

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

Steffen, W., Sanderson, A., Tyson, P. D., Jäger, J., Matson, P. A., Moore, B., III, Oldfield, F., Richardson, K., Schellnhuber, H. J., Turner, B. L., II, & Wasson, R. J. (Eds.). (2004). *Global change and the Earth system. A planet under pressure*. Berlin: Springer.

Steffen, W., Crutzen, P. J., & McNeill, J. R. (2007). The Anthropocene: Are humans now overwhelming the great forces of nature. *Ambio, 36*, 614–621.

Suh, S. (2005). Theory of materials and energy flow analysis in ecology and economics. *Ecological Modelling, 189*, 251–269.

Swartz, W., Sala, E., Tracey, S., Watson, R., & Pauly, D. (2010). The spatial expansion and ecological footprint of fisheries (1950 to present). *PLoS ONE, 5*, e15154.

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

van der Leeuw, S. E. (2004). Why model? *Cybernetics and Systems, 35*, 117–128.

Verburg, P. H., Chen, Y., & Veldkamp, T. (2000). Spatial explorations of land use change and grain production in China. *Agriculture, Ecosystems and Environment, 82*, 333–354.

Verburg, P. H., Neumann, K., & Nol, L. (2010). Challenges in using land use and land cover data for global change studies. *Global Change Biology, 17*, 974–989.

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

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H., & Tilman, D. G. (1997). *Human alteration of the global nitrogen cycle: Causes and consequences* (Issues in ecology, 1). Washington, DC: Ecological Society of America.

Vörösmarty, C. J., Sharma, K. P., Fekete, V. M., Copeland, A. H., Holden, J., Marble, J., & Lough, J. A. (1997). The storage and aging of continental runoff in large reservoir systems of the world. *Ambio, 26*, 210–219.

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.

Wang, T., Müller, D. B., & Graedel, T. E. (2007). Forging the anthropogenic iron cycle. *Environmental Science and Technology, 41*, 5120–5129.

Weiß, M., Schaldach, R., Alcamo, J., & Flörke, M. (2009). Quantifying the human appropriation of fresh water by African agriculture. *Ecology and Society*, *14,* 25. (Online] URL: http://www.ecologyandsociety.org/vol14/iss2/art25/

Weisz, H., & Duchin, F. (2006). Physical and monetary input-output analysis: What makes the difference? *Ecological Economics, 57*, 534–541.

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

Whittaker, R. H., & Likens, G. E. (1973). Primary production: The biosphere and man. *Human Ecology, 1*, 357–369.

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*, 189–194.