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Commentary

How a socio-ecological metabolism approach can help to advance our understanding of changes in land-use intensity

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1. Introduction

The quantity and quality of land use directly and indirectly relates to many "grand challenges" in sustainability science (Vitousek, 1997; Rindfuss et al., 2004; Global Land Project, 2005; Steffen et al., 2007; Turner et al., 2007). Land use is a major driver for habitat encroachment and biodiversity loss (Sala et al., 2000), for the alterations of global biogeochemical cycles (Gruber and Galloway, 2008; Postel et al., 1996; Vitousek et al., 1997) and for soil degradation (Lal, 2004). Changes in land use and subsequent changes in land cover play a central role in the global carbon cycle and significantly contribute to anthropogenic climate change (Brovkin et al., 2004; Canadell et al., 2007; McGuire et al., 2001; Watson et al., 2000). On the other hand, land use provides the nutritional basis for humans and thus of any socioeconomic system, and is intrinsically linked to food security (Ayres, 2007; Foley et al., 2005; Millennium Ecosystem Assessment, 2005).

Research on global land use has a long tradition, reaching back to the work of G.P. Marsh (1865) and A. Von Humboldt (1849). It gained momentum in sustainability research in the mid-1970s, when the impact of land use on the global surface albedo was recognized (Lambin et al., 2006). Since then, many aspects of land use have been assessed, quantified and mapped across spatio-temporal scales.

Two aspects of land use changes can be distinguished: (a) Changes in land cover, i.e. alterations of biophysical characteristics of the Earth's surface, e.g. by expansion or contraction of a certain land use type; a prominent example would be the expansion of agricultural fields into pristine forests. (b) Changes in land use intensity, denoting changes in the levels of socioeconomic inputs (e.g., labour, resources, water, energy or capital) and/or altered output (value or quantity) per unit area and time. Changes in intensity need not result in changes in land cover, but cause ecological changes within the same land cover type.

Increasing land use intensity stands in an inverse relation to land expansion for increasing production. Consequently, a major effect of intensification may be to "spare" land, e.g. for wilderness conservation, by concentrating production on other areas (Tilman, 2001). Indeed, this effect is often assumed to be essential for many sustainability aspects, as it allows to reduce area demand and avoid considerable carbon emissions from deforestation (Burney et al., 2010) or habitat encroachment (Green et al., 2005). In the future, safeguarding the land-sparing effect of intensification could become decisive, given the rising nutritional and energy demands of a growing world population, and the concomitant need to protect the shrinking untouched habitats of the Earth, rich in biodiversity and carbon. Moreover, many policies that aim at harnessing land use for the goals of climate change mitigation, such as strategies aimed at expanding bioenergy production, or at reducing greenhouse gas emissions from deforestation and forest degradation (REDD), will probably not be effective without the land sparing effect of intensification.

On the other hand, many technologies required for intensification are associated with detrimental ecological impacts, such as the accumulation of toxins in food, ecosystem and soil degradation, groundwater and air pollution, or biodiversity loss (IAASTD, 2009; Matson et al., 1997; Millennium Ecosystem Assessment, 2005; Tilman, 2001). Such processes negatively affect the ability of ecosystems to sustain vital ecosystem services, thereby running the risk of jeopardizing human well-being in the long run (Foley et al., 2005). Thus, it will become imperative to find ways of sustainable intensification (Tilman et al., 2002) that allow reaping its land-sparing benefits while at the same time avoiding the detrimental social and ecological effects.

However, the interrelation between intensification and expansion of land use is far from trivial. Empirical analyses of Rudel et al. (2009) on the interrelation between past trajectories in cropland expansion and intensification resulted in inconclusive findings. At the national scale, land use intensification was paired with a decline or stasis in cropland area between 1970 and 2005 only in countries that "externalized" agricultural production (e.g. grain imports) or preserved land with explicit land conservation programs (Rudel et al., 2009). These counterintuitive findings may be explained not only by large data gaps and uncertainties (Grainger, 2009), but also by feedback

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loops of higher order, such as a rebound effect of consumption to increased production, that overcompensated the land-sparing effect (Lambin and Meyfroidt, 2011). This altogether casts doubts on the straightforward interpretations or scenario-based extrapolations of the beneficial effects of land intensification strategies.

These feedback loops of land transitions are active across a wide range of spatial and temporal scales (Global Land Project, 2005; Lambin and Geist, 2005; Bennett and Balvanera, 2007; Erb et al., 2009b; Lambin and Meyfroidt, 2011). To take such feedbacks into account is indispensable, but it poses a formidable challenge to land change science (Turner et al., 2007), as it requires innovative methods and new perspectives that allow for the construction of sound causal chains between the various factors, mechanisms, determinants and constraints that underpin land-use intensification processes.

In this commentary, I discuss the potential contribution of an extension of the socioeconomic metabolism concept (Ayers and Simonis, 1994; Ayres, 1989; Fischer-Kowalski and Hüttler, 1998) by accounts that create an integrated picture of socio-ecological flows (Erb et al., 2008; Haberl et al., 2004; Krausmann et al., 2004) to global land system science. Such an approach could help to develop an analytical framework for conceptualizing and reporting on the complex, systemic interactions related to land use intensification, including feedbacks between production and consumption. It thus might give guidance for data collection and analysis, and so enhance the understanding of the interplay between land expansion and intensification.

2. Barriers to Understanding Land-Use Intensity

Immense research efforts are currently focusing on analyzing land cover changes and their role in the Earth system. Much fewer attempts exist to quantify and map changes in land use intensity, in particular at the global scale (Lambin et al., 2000, 2001). This is surprising, because land-use intensification represented a major focus of land use research in the past (Allen, 2001; Boserup, 1965; Brookfield, 2001; Netting, 1993; Shriar, 2000; Turner et al., 1977), but the attention paid to this aspect of land use change decreased in the last decades. However, changes in land use intensity are hugely important in terms of its socioeconomic as well as ecological effects, as global empirical analyses reveal (Tilman, 1999; Tilman et al., 2002): Since the early 1960s, intensification has brought about 2.7 fold increases in the global agricultural production of crucial products such as cereals, made possible by tremendous surges in agricultural inputs and new crop varieties. In contrast, harvested area, central focus of many land change studies or land-use transition conceptualizations, has remained almost stable (FAOSTAT, 2011; Fig. 1).

In my perception, the interplay of three major characteristics of the current mainstream in land-use research contributed to this changing focus of land-use research. These mutually interdependent aspects are the following.

1) The widespread availability of wall-to-wall fine-scale land-cover datasets, which are particularly abundant nowadays due to advances in remote sensing, draws attention on changes in land use that coincide with changes in land cover and subsequently distract from studies of other land use changes. Land cover data, i.e. data on the biophysical characteristics of Earth's surface, have been decisive for the progress of land use science (Turner et al., 2007), insofar as such studies have helped to depict land-use change as a process of global significance (Turner et al., 1990; Foley et al., 2005; Millennium Ecosystem Assessment, 2005, etc.). While widespread availability of land-cover data for land change research has brought the study of land-cover change into focus, it also diverted attention from the study of phenomena such as intensification, because most changes associated with intensification are not related to changes in land cover and thus not detectable by remote sensing (Verburg et al., 2011). Tellingly, such changes in land-use intensity are commonly referred to as “subtle” changes (Veldkamp and Lambin, 2001), despite the fact they can have far-reaching consequences, such as massive changes in greenhouse-gas emissions related to management changes on cropland or in the livestock sector (e.g. Steinfeld et al., 2006).
2) Methodologically, most studies of land use and land cover are based on classification systems that assign a discrete, homogenous land-use type (class) to each gridcell or polygon, i.e. they are based on nominal scales (Stevens, 1946). Thus, land-use change is conventionally measured as the change of the area and spatial distribution of land characterized by a well-defined combination of management and land cover, e.g. urban, crops, grazing or forestry. The advantage of such a basic approach is evident: area covered by a defined land-use class can be quantified, mapped, and thereby traced through space and time. Nominal-scale data allow analyzing

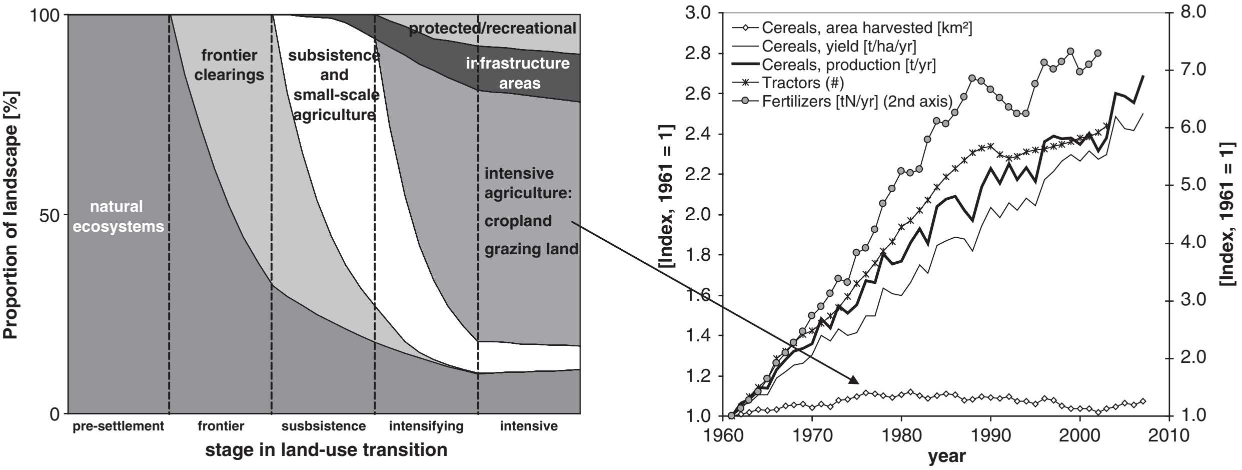

Fig. 1. Changes in land use intensity play an essential role in land-use transitions and can be more pronounced than changes in land cover. Global growth in the production of cereals since 1961 has depended almost exclusively on intensification (i.e. nitrogen input, tractors, yields and many other factors not shown here), whereas the expansion of harvested area has played an insignificant role. Please note that fertilizer consumption is drawn against the secondary axis. Sources: left: iconic scheme for conceptualizing land use transitions, redrawn after Foley et al. (2005), right: FAO 2007.

changes of areas covered by a defined land-use category, i.e. by the transition of a defined area of land from one class (e.g., grazing land) into another (e.g., cropland).
However, besides difficulties of unambiguous allocation and delineation (e.g. of agroforestry or grazing; Erb et al., 2007; Verburg et al., 2011), nominal scales are not well-suited to analyzing continuous, functional processes. Intensity changes entail changes within a land-use class that leads exactly to such processes. By their very nature, these processes need to be measured on ratio scales (Stevens, 1946), i.e. scales that measure the magnitude of continuous quantities (e.g., flow of energy or materials, work input etc.).

3) The intensity with which land is used is prominently influenced by socioeconomic processes, options and capabilities. Thus, natural science based approaches are not sufficient for conceptualizing, quantifying and understanding land-use intensity and intensification processes. While many social-science based studies on the processes and trajectories of land-use intensification exist, such data and analyses are scarce at the global scale (Liverman and Cuesta, 2008), possibly owing to the dominance of land cover data. However, in order to make progress in the field of land use intensification, genuinely integrated approaches are required, that combine knowledge from various disciplines in the social and natural sciences.

Some aspects of these shortcomings have already been identified and addressed in land use science so far, mainly offering partial solutions. For example, the intricacies related to nominal scales have been discussed for land cover datasets and led to the establishment of continuous field data (DeFries et al., 1995; Hansen et al., 2003). The need to counteract the under-representation of social sciences in research dealing with global environmental change is conceptually addressed in the seminal "socializing the pixel" research strand (Geoghegan et al., 1998; Rindfuss et al., 2004). Combinations of biophysical and socioeconomic information allowed to develop classification schemes of the land system in spatially explicit, socio-ecological terms, creating e.g. typologies of human–environment systems (Ellis and Ramankutty, 2008; Kruska et al., 2003; Leff et al., 2004). Such approaches have gained particular attention as they bring the integrated nature of the land system into focus (Alessa and Chapin, 2008; Verburg et al., 2009). However, these studies also suffer from the problems caused by using nominal scales, being unable to grasp gradients of land use intensity. Another strand of research aims at counterbalancing the dominance of land cover data by reconciling land-cover data with land use information from agricultural census statistics, with varying purposes and outcomes. Some of this research led to the generation of land-use maps (Erb et al., 2007; Goldewijk et al., 2007; Klein Goldewijk et al., 2011; Leff et al., 2004; Pongratz et al., 2009; Ramankutty et al., 2008; Siebert et al., 2005; Wood and Skole, 1998) which are widely used in studies of, e.g., the human impact on the global climate system (Verburg et al., 2011), but still focus on the extent of land use types, and not on the intensity of their use. A limited number of these land use datasets, however, present indeed information on aspects of land use intensity, such as crop yield per harvest event (Monfreda et al., 2008) or cropping intensity (number of crop harvests per year; Portmann et al., 2010; Siebert et al., 2010); these datasets, however, are restricted to cropland.

3. A Socio-Ecological Metabolism Approach to Land-Use Intensity

Approaches aimed at improving our understanding of land-use intensity, intensification and its interplay with socioeconomic area requirement, and land cover change require moving beyond simple accounts of the extent of selected land-use types.

As intensification denotes increase in socioeconomic inputs to and/or outputs from land, and thus closely refers to socioeconomic material or energy flows, the metabolism approach (Adriaanse et al., 1997; Ayres, 1989; Fischer-Kowalski and Haberl, 2007; Fischer-Kowalski and Hüttler, 1998; Schandl and Schulz, 2002) seems to be particularly suited to overcome some of the above-discussed barriers to understanding land use intensification.

This concept, adopted from biology (for a review see Fischer-Kowalski and Hüttler, 1998 and Schandl and Schulz, 2002) has gained attention in interdisciplinary research fields that fall under the umbrella of sustainability science (Clark and Dickson, 2003; Kates et al., 2001). It aims at the study of the biophysical (material and energy) exchange relationships between societies and their natural environment. The socioeconomic metabolism concept is embedded in a concept of socio-ecological systems that conceptualizes society as a hybrid of the cultural system of recursive communication, and biophysical structures such as the human population, artefacts and livestock. Interaction process between nature and culture can only proceed indirectly, via these biophysical structures of society. In consequence, sustainability can be understood as a characteristic of the interactions between society and nature (Haberl et al., 2004), and material and energy exchanges between social and natural systems become a vital element to observe, monitor and analyze (for a more elaborate exposition, see Fischer-Kowalski and Weisz, 1999 and Fischer-Kowalski and Rotmans, 2009).

The metabolism concept and its methodological tool box 'Material Flow Analysis' (MFA) allow for biophysical accounts of the socioeconomic system and so contribute to a 'reintegration of the natural sciences with economics' (Hall et al., 2001). The very strength of the metabolism concept is that it introduces an unambiguous and meaningful system boundary between social and natural systems, strictly following the law of conservation of mass, and consistently related to economic accounts. This has proven useful in guiding data collection and analyses, and MFA has recently been implemented in environmental reporting schemes of national and international institutions (EUROSTAT, 2001; OECD, 2008; Weisz et al., 2007).

MFA consistently collects, derives or models information on stocks and flows of material, energy or substances (e.g. carbon, nitrogen, water) between socioeconomic and natural systems. This feature bears already a high potential to study vital aspects of land intensification, as it allows for consistent accounts of socioeconomic inputs and outputs related to land use. In many studies on land-use intensification, two aspects of intensification are studied separately, despite the fact that they are intrinsically linked: (a) input intensification, i.e. attempts that analyze inputs to the land system., such as fertilizer, energy, or labour, and (b) output intensification, studying outputs of the land systems, such as cropland yields (Lambin et al., 2000; Shriar, 2000). Often, it is implicitly assumed that increases in inputs result in increased outputs, but empirical data to corroborate (or contradict) this belief is rare (Netting, 1993; Shriar, 2000). Notwithstanding said notion, systematically linking inputs to outputs yields remarkable insights into processes of intensification. For example, intensification in agrarian societies increases the productivity of land and reduces that of labour (Boserup, 1965; Chayanov, 1986). Industrialization changes this trend: labour productivity increases dramatically, but at the expense of deteriorating energy efficiency, as revealed by studies of the energy return on investments (EROI; i.e. the amount of energy output divided by energetics inputs; Pimentel et al., 1973; Krausmann et al., 2003).

However, the socioeconomic metabolism concept is not sufficient for studying the process of land use intensification in its entirety. Many aspects of land use intensification go beyond input or output flows, but directly relate to alterations of ecosystem properties. This requires an extension of the socioeconomic metabolism to a socio-ecological metabolism approach that consistently integrates ecological stocks and flows (also called "MEFA framework"; Haberl et al., 2004; Krausmann et al., 2004; Erb et al., 2008). Such an approach allows providing biophysical information on socioeconomic activities and linking this information to ecological processes in a meaningful manner.

The analytical strengths of the socio-ecological metabolism concept can be illustrated with the accounting framework and indicator 'human appropriation of net primary production' (HANPP; Vitousek et al., 1986; Haberl et al., 2007; Erb et al., 2009a). This indicator has attracted attention as a metric for the scope of the "human domination of ecosystems" (Vitousek, 1997). HANPP integrates two distinct effects of land use on one of the most fundamental ecological process, i.e. the flow of carbon or energy, in one account: (a) human-induced changes in productivity due to land conversions and (b) biomass harvest. The latter is a widely used surrogate indicator for output intensification in agriculture (see Neumann et al., 2010). The integration of this output intensification parameter with the associated land-use related alterations of ecological flows allows for two distinct perspectives at the same time: an ecological perspective that quantifies and monitors impacts on ecological flows on basis of a comparison of the hypothetical natural ('undisturbed') with the actually prevailing state. And a socioeconomic perspective that observes the amount of biomass gained from ecosystem, i.e. the provision of ecosystem services, as well as the associated collateral flow of energy, i.e. the unintended productivity losses due to land conversions. This integration of socioeconomic and biophysical perspectives (Krausmann et al., 2009) renders HANPP a useful framework to analyze drivers as well as impacts of changes in land-systems, in particular the link between biomass production and biomass consumption across scales (Erb et al., 2009b; Haberl et al., 2009a; Imhoff et al., 2004).

However, the focus of HANPP on energy flows alone is not sufficient when studying land-use intensification. Other aspects of intensification, such as the frequency of crop rotation cycles or alterations of ecosystem structures, have to be taken into account. Nevertheless, as HANPP provides un-weighted accounts of energy, biomass or carbon flows in the ecological and socioeconomic systems, it can be consistently integrated with such information (see e.g. Erb et al., 2008).

Socio-ecological analyses are not restricted to a certain spatial scale, but have been used to study society–nature interactions across a wide range of scales, from the global (Haberl et al., 2007) to the local level (Grünbühel et al., 2003; Singh et al., 2001) and so allow for nested approaches. Furthermore, the stringent system boundary and data on flows between different compartments in natural and socioeconomic systems have been found to be well-suited starting points for the develop agent-based models, able to scrutinize the role of local decision making in the land system (Gaube et al., 2009; Haberl et al., 2009b) These features render the metabolism approach predestined to study interrelations between decision-making, institutions, social, economic and political framework conditions, land-use change and biophysical flows, important for sustainability science's quest for sustainable solutions (Ostrom, 2007).

A socio-ecological metabolism approach allows studying the full cycle of land-use intensification, including its feedbacks (Fig. 2): Socioeconomic inputs to ecosystems, structural changes within ecosystems, and changes in outputs of ecosystems to society, as well as the underlying socioeconomic cost–benefit relations, constraints, feedbacks, and thresholds. An example from the seminal work by E. Boserup (1965) can be used to illustrate these interlinkages: shorter cropping cycles in swidden agriculture, resulting from higher population numbers and increased food demand, prevent natural forest ecosystems from fully recovering from shifting cultivation and so gradually lead to a dominance of herbaceous cover; this renders the use of clearing fires ineffective and, consequently, makes the use of

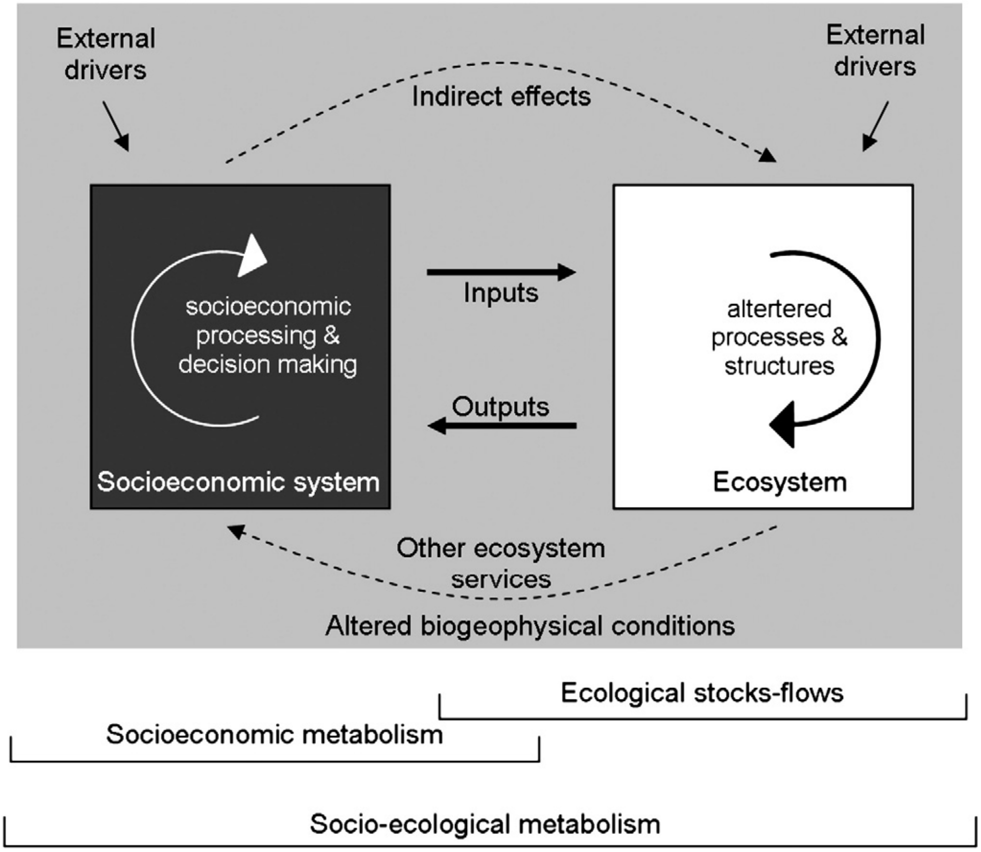

Fig. 2. Conceptual framework for research on land-use intensity. Socioeconomic and ecological systems are coupled through direct input and output flows (input and output intensification) and indirect effects, such as alterations of biogeophysical conditions or effects on the availability and quality of other ecosystem services not related to output, or indirect socioeconomic impacts on the natural systems, such as changes in atmospheric conditions. While natural science approaches focus on patterns and dynamics of ecosystem processes, social science approaches focus on patterns, dynamics and organization of socioeconomic systems. Only integrated approaches such as a socio-ecological metabolism approach are able to grasp the full cause–effect chains related to land-use intensification.

other technologies such as the hoe or plough necessary. These changes, in turn, trigger socioeconomic changes, such as the augmented provision of resources that may allow for a larger population, but also trigger changes in social organization, e.g. those that accompany the transition from hunter and gatherers to sedentary agriculture. Socioeconomic effects not related to land-use, as well as external perturbations, play an equally important role in this cycle, for example the human-induced increases in atmospheric CO_2 or the occurrence of droughts (Verstraete et al., 2009).

The strength to take these feedback loops between society and ecosystems into account can be illustrated taking the forest transition (Kauppi et al., 2006; Mather, 1992; Rudel et al., 2005), a phenomenon that denotes the return of forests after periods of deforestation in many countries, as an example. Whereas a straightforward interpretation of this phenomenon would stress the "improved" environmental performance, e.g. at the national scale, such as the associated considerable carbon sink, a socio-ecological metabolism approach would allow to scrutinize the related feedback loops and underlying mechanisms: agricultural intensification (Erb et al., 2008) or externalization effects due to trade (Kastner et al., 2011; Meyfroidt et al., 2010) reduce domestic area demand that allows for forest re-growth. Thus, the emerging carbon sink is not result of an explicit land use strategy, but part of a baseline development in many countries, intrinsically build upon the availability of (cheap) fossil fuels. Moreover, the biophysical focus allows to study aspects that cannot be captured with mere economic accounts, such as biophysical constraints, minimum nutritional levels, or overconsumption and their effects to human health (de Boer and Aiking, 2011).

Table 1 gives some examples to illustrate how a socio-ecological metabolism approach might allow identifying systemic interrelations of a higher order, such as problem shifts or rebound effects, relevant for forging sustainable strategies around land use.

4. Outlook and Conclusions

The formulation of land use strategies aimed at harnessing beneficial aspects of land use for sustainability goals needs to be based on a thorough understanding of the underlying mechanisms and driving forces, taking the spatial and temporal interrelation of the different feedback loops into account.

Many mechanisms and processes of essential aspects of land-use transitions remain under-researched to date. Neither databases nor conceptualizations are currently available at sufficient quality and quantity to allow for integrated analyses of land-use intensification. The socio-ecological metabolism concept allows to generate comprehensive accounts, including direct (e.g. metabolic) and indirect (e.g. alterations of ecosystem structures) interactions between society and ecosystems as well as their feedbacks. Such accounts have a high potential to contribute to bridging the critical chasm between social and natural sciences related to global environmental change research (Liverman and Cuesta, 2008), as they integrate socioeconomic as well as ecological processes.

A socio-ecological metabolism approach could significantly contribute to the many ongoing initiatives dedicated to the observation and monitoring of the Earth system, such as the Global Earth Observing System of Systems (GEOSS), Global Terrestrial Observing system (GTOS), or the Integrated Global Observing System (IGOS; to name but a few), that currently struggle with the many requirements related to the establishment of an integrated, comprehensive and sustained earth observing system (Grainger, 2009; Turner, 2011). Increasing the spatial resolution of the existing observing systems and sensors is, often implicitly, suggested as a response to these challenges. Such efforts, however, although promising in many instances, will not only be cost-intensive in terms of data acquisition, handling and interpretation, but are also not well-suited to operationalise land use intensity. A metabolism approach, in contrast, would allow introducing a complementary, integrated perspective, as well as a stringent system boundary that is well-suited to inform and guide data collection and analysis on critical dimensions of land use transitions.

The need for interdisciplinary perspectives is growing, as the grand sustainability challenges are. The metabolism concept provides analytical tools that allow to advance our systemic understanding of the many trade-offs related to land use intensification, placed at the very heart of ecosystem functioning and human well-being. These improvements of our understanding are a prerequisite for forging strategies that aim at reaping the benefits of land intensification while simultaneously avoiding detrimental social and ecological effects.

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Table 1
The strength of the socio-ecological metabolism approach, illustrated with examples of current land use strategies.

Land use strategy	Intended benefit	Caveat introduced by a socio-ecological perspective
Land use intensification	Allows land sparing, benefits for biodiversity, carbon sequestration/conservation (see e.g. Green et al., 2005; Burney et al., 2010)	Intensification can result in increased consumption due to increased resource availability, triggering further land use intensification and expansion. Allows to generate a more realistic counterfactual to the assumption that consumption levels would stay the same in the light of altered production.
Organic farming	Reduces resource use, in particular of non-renewable resources, reduced carbon emissions	If not paired with reduced consumption, the increased area demand of organic farming can reverse the carbon saving effect, by triggering deforestation or reduce afforestation/regeneration, increased climate impact.
Bioenergy	Substitutes for fossil energy, reduces emissions	Conflict with other land uses; land expansion/deforestation elsewhere, thus increased global emissions; impacts upon food security, in particular of population living from subsistence agriculture.
Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD)	Reduce carbon emissions, generate income in rural communities	Land use conflicts can result in considerable leakage and intensification/ land expansion elsewhere. Might decrease net income, self-sufficiency and food security in rural areas due to increased dependency on external markets. Additionality and permanence depending on drivers and constraints of land use intensification in non-forested ecosystems.

References

Adriaanse, A., Bringezu, S., Hammond, A., Moriguchi, Y., Rodenburg, E., Rogich, D., Schütz, H., 1997. Resource Flows: The Material Basis of Industrial Economies. World Resources Institute, Washington, D.C.

Alessa, L., Chapin III, F.S., 2008. Anthropogenic biomes: a key contribution to earth-system science. Trends in Ecology & Evolution 23, 529–531.

Allen, B.J., 2001. Boserup and Brookfield and the association between population density and agricultural intensity in Papua New Guinea. Asia Pacific Viewpoint 42, 236–254.

Ayers, R.U., Simonis, U.E., 1994. Industrial Metabolism: Restructuring for Sustainable Development. United Nations University Press, Tokyo.

Ayres, R.U., 1989. Industrial Metabolism. National Academy Press, Washington, DC.

Ayres, R.U., 2007. On the practical limits to substitution. Ecological Economics 61, 115–128.

Bennett, E.M., Balvanera, P., 2007. The future of production systems in a globalized world. Frontiers in Ecology and the Environment 5, 191–198.

Boserup, E., 1965. The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure. Earthscan, London.

Brookfield, H., 2001. Intensification, and alternative approaches to agricultural change. Asia Pacific Viewpoint 42, 181–192.

Brovkin, V., Sitch, S., Von Bloh, W., Claussen, M., Bauer, E., Cramer, W., 2004. Role of land cover changes for atmospheric CO_2 increase and climate change during the last 150 years. Global Change Biology 10, 1253–1266.

Burney, J.A., Davis, S.J., Lobell, D.B., 2010. Greenhouse gas mitigation by agricultural intensification. Proceedings of the National Academy of Sciences 107, 12052–12057.

Canadell, J.G., Le Quéré, 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 CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences 104, 18866–18870.

Chayanov, A.V., 1986. The Theory of Peasant Economy, 1st ed. University of Wisconsin Press.

Clark, W.C., Dickson, N.M., 2003. Sustainability science: the emerging research program. Proceedings of the National Academy of Sciences 100, 8059–8061.

de Boer, J., Aiking, H., 2011. On the merits of plant-based proteins for global food security: marrying macro and micro perspectives. Ecological Economics 70, 1259–1265.

DeFries, R.S., Field, C.B., Fung, I., Justice, C.O., Los, S., Matson, P.A., Matthews, E., Mooney, H.A., Potter, C.S., Prentice, K., Sellers, P.J., Townshend, J.R.G., Tucker, C.J., Ustin, S.L., Vitousek, P.M., 1995. Mapping the land surface for global atmosphere–biosphere models: toward continuous distributions of vegetation's functional properties. Journal of Geophysical Research 100, 20,867–20,882.

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., Gaube, V., Krausmann, F., Plutzar, C., Bondeau, A., Haberl, H., 2007. A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. Journal of Land Use Science 2, 191–224.

Erb, K.-H., Gingrich, S., Krausmann, F., Haberl, H., 2008. Industrialization, fossil fuels, and the transformation of land use. 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., Lucht, W., Haberl, H., 2009b. Embodied HANPP: mapping the spatial disconnect between global biomass production and consumption. Ecological Economics 69, 328–334.

EUROSTAT, 2001. Economy-wide Material Flow Accounts and Derived Indicators. A Methodological Guide. Eurostat, European Commission, Office for Official Publications of the European Communities, Luxembourg.

Faostat, F., 2011. Statistical Databases.

Fischer-Kowalski, M., Haberl, H., 2007. Socioecological transitions and global change: trajectories of social metabolism and land use. Edward Elgar Publishing.

Fischer-Kowalski, M., Hüttler, W., 1998. Society's metabolism. Journal of Industrial Ecology 2, 107–136.

Fischer-Kowalski, M., Rotmans, J., 2009. Conceptualizing, observing and influencing socio-ecological transitions. Ecology and Society: A Journal of Integrative Science for Resilience and Sustainability 1–18.

Fischer-Kowalski, M., Weisz, H., 1999. Society as hybrid between material and symbolic realms: toward a theoretical framework of society–nature interaction. Advances in Human Ecology 8, 215–252.

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., et al., 2005. Global consequences of land use. Science 309, 570.

Gaube, V., Kaiser, C., Wildenberg, M., Adensam, H., Fleissner, P., Kobler, J., Lutz, J., Schaumberger, A., Schaumberger, J., Smetschka, B., Wolf, A., Richter, A., Haberl, H., 2009. Combining agent-based and stock-flow modelling approaches in a participative analysis of the integrated land system in Reichraming, Austria. Landscape Ecology 24, 1149–1165.

Geoghegan, J., Pritchard, L.J., Ogneva-Himmelberger, Y., Chowdhury, R.R., Sanderson, S., Turner, B.L., 1998. Socializing the pixel" and "pixelizing the social" in land-use and land-cover change. In: Liverman, D.M., Moran, E., Rindfuss, R.R., Stern, P. (Eds.), People and Pixels. Linking Remote Sensing and Social Science. National Academy Press, Washington, D.C., pp. 51–69.

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, 167–190.

Grainger, A., 2009. Measuring the planet to fill terrestrial data gaps. Proceedings of the National Academy of Sciences 106, 20557–20558.

Green, R.E., Cornell, S.J., Scharlemann, J.P.W., Balmford, A., 2005. Farming and the fate of wild nature. Science 307, 550–555.

Gruber, N., Galloway, J.N., 2008. An Earth-system perspective of the global nitrogen cycle. Nature 451, 293–296.

Grünbühel, C.M., Haberl, H., Schandl, H., Winiwarter, V., 2003. Socioeconomic metabolism and colonization of natural processes in Sangsaeng village: material and energy flows, land use, and cultural change in Northeast Thailand. Human Ecology 31, 53–86.

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H., Winiwarter, V., 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy 21, 199–213.

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 104, 12942–12947.

Haberl, H., Erb, K.H., Krausmann, F., Berecz, S., Ludwiczek, N., Martínez-Alier, J., Musel, A., Schaffartzik, A., 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.

Hall, C., Lindenberger, D., KüMmel, R., Kroeger, T., Eichhorn, W., 2001. The need to reintegrate the natural sciences with economics. BioScience 51, 663.

Hansen, M., DeFries, R., Townshend, J., Carroll, M., Dimiceli, C., Sohlberg, R., 2003. Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS vegetation continuous fields algorithm. Earth Interactions 7, 1–15.

IAASTD, 2009. Agriculture at as crossroad. International assessment of agricultural knowledge, science and technology for development. Global Report. Island Press, Washington, D.C.

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, 870–873.

Kastner, T., Erb, K.H., Nonhebel, S., 2011. International Wood Trade and Forest Change: A Global Analysis. Global Environmental Change.

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., Mooney, H., Moore, B., O'Riordan, T., Svedin, U., 2001. Sustainability science. Science 292, 641–642.

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 103, 17574–17579.

Klein Goldewijk, K., Beusen, A., van Drecht, G., de Vos, M., 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Global Ecology and Biogeography 20, 73–86.

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, 1–20.

Krausmann, F., Haberl, H., Erb, K.-H.K.-H., Wackernagel, M., 2004. Resource flows and land use in Austria 1950–2000: using the MEFA framework to monitor society–nature interaction for sustainability. Land Use Policy 21, 215–230.

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, 15–33.

Kruska, R.L., Reid, R.S., Thornton, P.K., Henninger, N., Kristjanson, P.M., 2003. Mapping livestock-oriented agricultural production systems for the developing world. Agricultural Systems 77, 39–63.

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

Lambin, E.F., Geist, H.J., 2005. Land Use and Land Cover Change: Local Processes. Global Impacts, Springer, Berlin.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences 108, 3465–3472.

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 & Environment 82, 321–331.

Lambin, E.F., Turner, B.L., 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., Skånes, 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.

Lambin, E.F., Geist, H., Rindfuss, R.R., 2006. Introduction: local processes with global impacts. Land-Use and Land-Cover Change. Springer, Berlin, pp. 1–8.

Land Project, Global, 2005. Science plan and implementation strategy. IGBP Report 53/IHDP Report 19. IGBP Secretariat, Stockholm.

Leff, B., Ramankutty, N., Foley, J.A., 2004. Geographic distribution of major crops across the world. Global Biogeochemical Cycles 18, 16.

Liverman, D.M., Cuesta, R.M.R., 2008. Human interactions with the Earth system: people and pixels revisited. Earth Surface Processes and Landforms 33, 1458–1471.

Marsh, G.P., 1865. Man and Nature: Or, Physical Geography as Modified by Human Action. Scribner.

Mather, A.S., 1992. The forest transition. Area 24, 367–379.

Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural intensification and ecosystem properties. Science 277, 504–509.

McGuire, A.D., Sitch, S., Clein, J.S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D.W., Meier, R.A., Melillo, J.M., Moore, 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 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 107, 20917–20922.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Current State and Trends, Volume 1. Island Press, Washington, D.C.

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochemical Cycles 22, 1–19.

Netting, R.M.C., 1993. Smallholders, Householders: Farm Families and the Ecology of Intensive, Sustainable Agriculture. Stanford Univ Pr.

Neumann, K., Verburg, P.H., Stehfest, E., Müller, C., 2010. The yield gap of global grain production: a spatial analysis. Agricultural Systems 103, 316–326.

OECD, 2008. Measuring material flows and resource productivity. Synthesis Report. Organisation for Economic Co-operation and Development, Paris.

Ostrom, E., 2007. A diagnostic approach for going beyond panaceas. Proceedings of the National Academy of Sciences 104, 15181–15187.

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.

Pongratz, J., Reick, C., Raddatz, T., Claussen, M., 2009. Effects of anthropogenic land cover change on the carbon cycle of the last millennium. Global Biogeochemical Cycles 23, GB4001.

Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000—global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. Global Biogeochemical Cycles 24, GB1011.

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

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.

Rindfuss, R.R., Walsh, S.J., Turner, B.L., Fox, J., Mishra, V., 2004. Developing a science of land change: challenges and methodological issues. Proceedings of the National Academy of Sciences of the United States of America 101, 13976–13981.

Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J., Lambin, E., 2005. Forest transitions: towards a global understanding of land use change. Global Environmental Change Part A 15, 23–31.

Rudel, T.K., Schneider, L., Uriarte, M., Turner, B.L., DeFries, R., Lawrence, D., Geoghegan, J., Hecht, S., Ickowitz, A., Lambin, E.F., Birkenholtz, T., Baptista, S., Grau, R., 2009. Agricultural intensification and changes in cultivated areas, 1970–2005. Proceedings of the National Academy of Sciences 106, 20675–20680.

Sala, O.E., Stuart Chapin III, F., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, 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.H., Walker, M., Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. Science 287, 1770–1774.

Schandl, H., Schulz, N., 2002. Changes in the United Kingdom's natural relations in terms of society's metabolism and land-use from 1850 to the present day. Ecological Economics 41, 203–221.

Shriar, A., 2000. Agricultural intensity and its measurement in frontier regions. Agroforestry Systems 49, 301–318.

Siebert, S., Döll, P., Hoogeveen, J., Faures, J.-M., Frenken, K., Feick, S., 2005. Development and validation of the global map of irrigation areas. Hydrology and Earth System Sciences 9, 535–547.

Siebert, S., Portmann, F.T., Döll, P., 2010. Global patterns of cropland use intensity. Remote Sensing 2, 1625–1643.

Singh, S.J., Grünbühel, C.M., Schandl, H., Schulz, N., 2001. Social metabolism and labour in a local context: changing environmental relations on Trinket Island. Population and Environment 23, 71–104.

Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The Anthropocene: are humans now overwhelming the great forces of nature? Ambio: A Journal of the Human Environment 36, 614–621.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's Long Shadow: Environmental Issues and Options. FAO/LEAD, Rome, Italy.

Stevens, S.S., 1946. On the theory of scales of measurement. Science 103, 677–680.

Tilman, D., 1999. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proceedings of the National Academy of Sciences 96, 5995.

Tilman, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Turner, D.P., 2011. Global vegetation monitoring: toward a sustainable technobiosphere. Frontiers in Ecology and the Environment 9, 111–116.

Turner, B.L., Hanham, R.Q., Portararo, A.V., 1977. Population pressure and agricultural intensity. Annals of the Association of American Geographers 67, 384–396.

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

Turner, 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 104, 20666–20671.

Veldkamp, A., Lambin, E.F., 2001. Predicting land-use change. Agriculture, Ecosystems & Environment 85, 1–6.

Verburg, P.H., van de Steeg, J., Veldkamp, A., Willemen, L., 2009. From land cover change to land function dynamics: a major challenge to improve land characterization. Journal of Environmental Management 90, 1327–1335.

Verburg, P.H., Neumann, K., Nol, L., 2011. Challenges in using land use and land cover data for global change studies. Global Change Biology 17, 974–989.

Verstraete, M.M., Scholes, R.J., Smith, M.S., 2009. Climate and desertification: looking at an old problem through new lenses. Frontiers in Ecology and the Environment 7, 421–428.

Vitousek, P.M., 1997. Human domination of earth's ecosystems. Science 277, 494–499.

Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., Matson, P.A., 1986. Human appropriation of the products of photosynthesis. BioScience 36, 368–373.

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: sources and consequences. Ecological Applications 7, 737–750.

Von Humboldt, A., 1849. Cosmos: a sketch of a physical description of the universe. HG Bohn.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N., Verardo, D.J., Dokken, D.J., 2000. Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change. Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change.

Weisz, H., Krausmann, F., Eisenmenger, N., Schütz, H., Haas, W., Schaffartzik, A., 2007. Economy-wide material flow accounting. A Compilation Guide. Eurostat, European Commission, Luxemburg.

Wood, C.H., Skole, D., 1998. Linking satellite, census, and survey data to study deforestation in the Brazilian Amazon. In: Liverman, D.M., Moran, E.F., Rindfuss, R.R., Stern, P. (Eds.), People and Pixels: Linking Remote Sensing and Social Science. National Academy Press, Washington, D.C., pp. 70–93.