

Indicators of Sustainable Land Use - Concepts for the Analysis of Society-Nature Interrelations and Implications for Sustainable Development

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Abstract

Current attempts to develop comprehensive systems of sustainability indicators based upon the usual "pressure-state-response" (PSR) framework failed to yield convincing results, mainly due to the narrow focus of PSR on traditional environmental policy. We here propose an extended system of sustainability indicators containing four types of indicators: (1) Socio-economic driving forces, (2) pressures on the environment, (3) states of the environment, and (4) impacts of environmental change on society. This indicator typology is based upon a conceptual process model of the interaction society-nature, envisaging society and nature as autopoietic, interacting systems. The model was developed within an interdisciplinary team and can serve as a framework for the analysis of environmental problems in joint efforts of scientists from social and natural sciences, and the humanities. As tools for the empirical analysis of society-nature-interrelations we propose to use two basic concepts: (1) Socio-economic metabolism, i.e. the material and energy flows between socio-economic systems and their natural environment. (2) The colonization of nature, i.e. the conundrum of deliberate interventions into natural systems aimed at their "improvement" with respect to socio-economic goals. While metabolism is closely connected with the quickly evolving paradigm of industrial ecology, colonization appears to be a good concept to develop indicators for socio-economic activities related to land use and land cover change. We also discuss empirical examples for such indicators with a focus on landscape-relevant indicators and attempt to relate land use with material and energy flow analysis.

Keywords: Sustainable development, indicators, human dimensions of environmental change, socio-economic metabolism, colonization of nature, land use, industrial ecology.

1. Introduction

In stimulating and provoking dialogue between various scientific disciplines and conflicting political and social groups, the concept of "sustainable development" has emerged as a fruitful approach for bringing together the social, economic, political, and ecological dimensions of global environmental problems in the last decade. The notion may be traced back to the German word "nachhaltige Forstwirtschaft" ("sustainable forestry") coined in the 18th century by von Carlowitz to denote forest management practices preserving forest stocks. The notion "sustainable development" was first used in the "World Conservation Strategy" developed by the International Union for the Conservation of Nature (IUCN), published in 1980 (Kopfmüller 1993).

There are numerous definitions and interpretations of sustainable development. Today, after more than a decade of attempts to define the concept, it appears that a scientific consensus on the meaning of the term "sustainable development" is not in sight and that it should be regarded as a political goal rather than a scientific notion. One essential point is that sustainable development aims at shaping the socio-economic behavior towards nature in ways that guarantee the preservation of the life-supporting natural systems for future generations. Sustainable development also seeks to achieve some kind of „global justice“ with respect to the distribution of natural resources.

Even in the absence of a generally accepted scientific definition, however, it seems to be generally agreed upon that sustainability encompasses socio-economic as well as ecological dimensions and aims at sustaining viable exchange processes between socio-economic systems and their natural environment (SRU 1998). As a consequence, interdisciplinary approaches are needed for sustainability research. While the development of binding criteria of sustainable development with respect to the social, economic, and ecological dimension of sustainability requires value judgements beyond the realm of scientific endeavour, interdisciplinary approaches can contribute to sustainable development in numerous ways, e.g. by analyzing the relations between socio-economic dynamics, socio-economic pressures on the environment, the changing state of natural systems, and the feedbacks of environmental change to society.

Research on the human dimensions of global environmental problems ("Global Change") centers around two aspects of society-nature relations:

1. Socio-economic or industrial metabolism: The study of material and energy flows associated with socio-economic activities (Boyden 1992, Ayres and Simonis 1994, Adriaanse et al. 1997, Erkmann 1997, Fischer-Kowalski 1997, 1998, Hüttler et al. 1997, Schandl 1998).

2. Land use and cover change: The analysis of human land use and its consequences for the changing patterns of land cover on various spatial and temporal scales (Turner et al. 1993, Meyer and Turner 1994, Meyer 1996).

In this paper we will attempt to show how these two currently quite unrelated problems may be put in a common perspective within sustainability indicator systems. We will proceed as follows: We start with a short review of sustainability indicators and indicator systems, put forward a proposal for categorizing sustainability indicators, and show some selected examples for indicators which are able to narrow the gap between industrial metabolism and land use and cover change.

2. Concepts for sustainability indicators: Examples from the literature

A currently widely used approach for operationalizing sustainability is the development of indicators. The need for indicator systems as a tool of evaluating progress towards sustainability was stated in the Agenda 21, adopted by the UN conference on environment and development (UNCED) in Rio de Janeiro 1992, and has led to several international and national initiatives for the development of indicator systems as well as to an increased scientific research aimed at proposing sustainability indicators. There are several international initiatives for the development of sustainability and environmental indicators (OECD 1994, Munasinghe and Shearer 1995, Moldan et al. 1997).

The term indicator traces back to the Latin verb *indicare*, meaning to disclose or point out, to announce or make publicly known, to estimate or put a price on (Hammond et al. 1995). Indicators of sustainable development have three main functions (Moldan et al. 1997, Bossel 1996): (1) *Simplification* - they supply information on the state of a system which is too complex to be assessed or measured directly; (2) *quantification*; and (3) *communication*. The development of indicators of sustainable development appears to be decisive for progress towards sustainable development (Moldan et al. 1997).

Indicators present information in quantitative form and allow the description of complex social, political, public, or natural processes. They thus can be seen as an empirical model of reality (Bossel 1996, Hammond et al. 1995). Indicators of sustainable development should describe progress towards sustainable development. Indicators of sustainable development thus - implicitly or explicitly - reflect some model of the interaction between societies and their natural environment.

These properties are, however, only loosely linked with the ecological impact of socio-economic systems. It has therefore been proposed to extend the usual economic accounting framework in or-

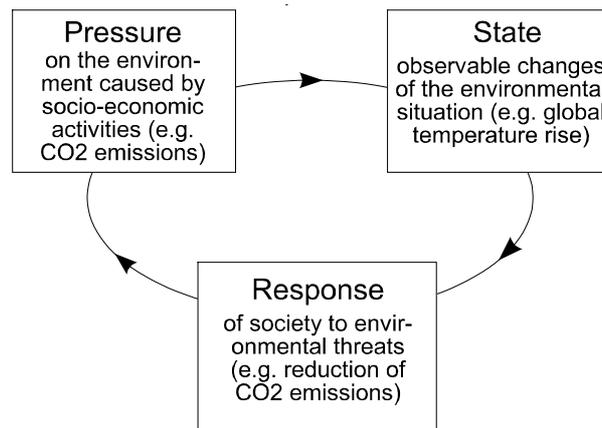
der to be able to account for environmental aspects of the economic process. This has taken two forms: (1) An attempt to integrate all kinds of ecological aspects in a "corrected" GNP value by "monetizing" the ecological impacts of the economy and including losses of resources stocks or environmental damages in the calculations within a reformed System of National Accounts (SNA). (2) The construction of so-called environmental satellite systems to the SNA, i.e. the accomplishment of the SNA with a set of environmental indicators, showing the overall environmental performance of the economy (United Nations 1993, El Serafy 1997, Uno and Bartelmus 1998). While several still unresolved fundamental questions hamper the idea of generating a unique combined ecological and economic accounting framework (Norgaard 1989), in the last years there has been an increased interest in the development of environmental indicators which may be used to construct "environmental satellite" accounts to the SNA (Bossel 1996, Hammond et al. 1996, Munasinghe and Shearer 1995, OECD 1994).

2.1 Comprehensive indicator systems: The Pressure-State-Response scheme

A recent review by the German Scientific Council on the Environment (SRU 1998) revealed that most approaches for environmental and sustainability indicators rely on the Pressure-State-Response (PSR) scheme put forward by the OECD (1994). The PSR scheme distinguishes three levels of analysis of environmental problems: (1) The *pressures* a society exerts on the environment (indicators for pressures on the environment), (2) how good or bad the *state* of the environment is (state indicators), and (3) which measures a society undertakes to improve either the environment (repair strategies) or its behavior towards the environment (*response* indicators). The PSR scheme implies a (cyclical) cause-effect-relationship (Figure 1) and is currently widely used by regional, national, and international organizations (UNO, ECE, OECD, EU).

The PSR scheme has been and still is successfully applied for the development of systems of environmental indicators which can be used for environmental information systems (e.g. the OECD environmental indicators or environmental statistics) and is also useful for environmental accounting (e.g. Uno and Bartelmus 1998). However, the PSR scheme has severe shortcomings for the development of comprehensive systems of sustainability indicators. For example, the recent SRU review has concluded that there are currently no successful examples for sustainability indicator systems based upon the PSR approach. All current approaches underrepresent the social and economical dimensions of sustainable development and are unable to relate these dimensions to the ecological dimension in a meaningful way (SRU 1998). Moreover, generally accepted sustainability criteria are lacking for most indicators.

Figure 1: The Pressure-State-Response scheme as a cyclical cause-effect relationship



Source: Bittermann and Haberl 1998 after OECD 1994

2.2 Indicators relating material flows to land use: Footprints and the SPI

There are two current approaches for environmental indicators which relate industrial metabolism, i.e. socio-economic material and energy flows, with land use: The Ecological Footprint (EFP) concept put forward by Wackernagel and Rees (1995) and the Sustainable Process Index (SPI) developed by Krotschek and Narodoslowsky (1996). The basic assumption of both concepts is that solar exergy is the only sustainable basis of an economy. The conversion of this exergy to services needs area. Area may thus be regarded as the main limiting factor for a sustainable economy. The material consumption of the population in a country (in the case of the EFP) or the materials and energy needed for an industrial process (SPI) may thus be converted into the area needed to sustainably maintaining the related material and energy flows.

According to this approach, material and energy flows need area mainly for two functions: (1) For the production of the resources and (2) for the deposition of wastes and by-products. Additionally, the area used for the necessary infrastructure (transport, housing etc.) is also taken into account. The use of fossil fuels may be converted to area with several approaches, e.g. by computing the area needed to sustainably produce the equivalent amount of fuel on the basis of biomass or by calculating the area needed to sequester the amount of emitted carbon dioxide by afforestation. If the methodology is applied to a national state, "imported" areas and domestically used areas may be distinguished. The EFP/SPI concept adds two different types of land use: (1) direct use of land for production, infrastructure, and deposition, and (2) "hypothetical" land use, based on the premise that CO₂ enrichment in the atmosphere is unsustainable.

The EFP concept also allows a comparison between the amount of productive area available per person (on every suitable regional level) and the amount of area needed to sustain current patterns of resource use, also on a per capita basis. Put more theoretically, the footprint concept allows the appraisal of two features of industrial metabolism: (1) The use of fossil fuels and the mobilization of mineral resources on a large scale reduces the area needed per unit of material throughput. The use of fossil fuels delinks energy use from the amount of actually available area (which is needed if a society relies more or less exclusively on biomass taken from actual ecological cycles through agriculture, hunting, and forestry). (2) The fact that modern transport technology and infrastructure have delinked land use from the place of the consumption of the resources for which the land is needed, thus allowing nations to consume more land than they dispose of.

3. Metabolism and Colonization: A theory guided approach towards environmental indicators

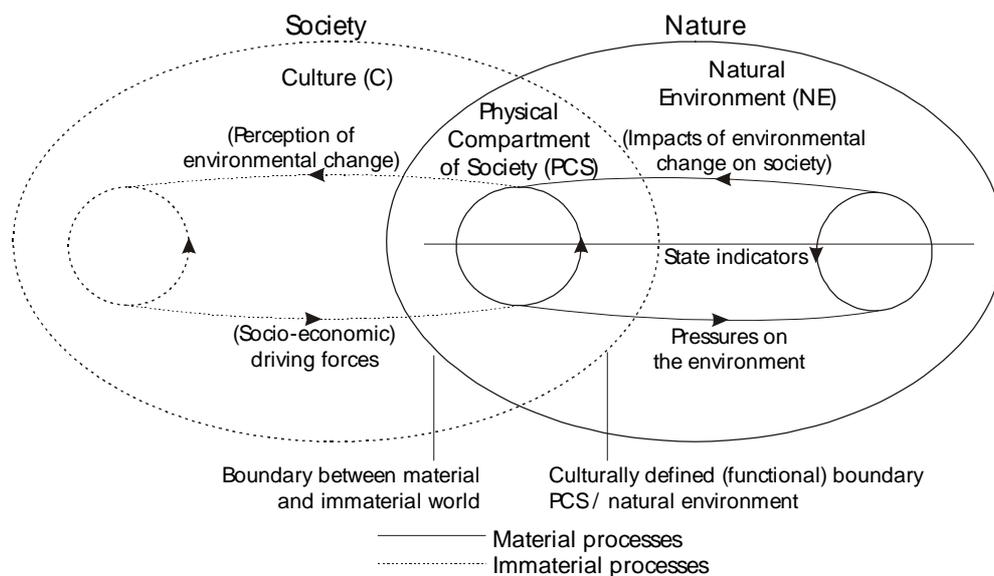
Research aimed at understanding the interrelations between social and natural systems, and thus sustainability research, is hampered by traditions in the social and natural sciences which tend to neglect or even deny such interrelations altogether. For example, most macrosociological theories envisage human societies as purely symbolic systems, e.g. as systems of communication (Luhmann 1986) or cultural meanings. Natural sciences, on the other hand, usually draw a sharp dividing line between their objects of study and the human agency.

3.1 A conceptual model for society-nature interrelations

If we accept the view that sustainability refers to society-nature interactions (and not to either natural or socio-economic systems in isolation), it follows that any study on problems of sustainable development must find some way to deal with this fundamental gap. This means that it is necessary to find a conceptual model for society-nature interrelationships which is able to serve as a common framework for interdisciplinary work of social and natural sciences. If we simply start with the premise that socio-economic and natural systems interact, we may conclude that there must be some touching sphere, or agents of interaction, between them (Boyden 1992, Knoflacher 1997, Sieferle 1997a,b). We may look upon this as a part of nature in which most material and energetic processes are governed by societal regulation, and we may, quite as well, regard it as a "physical compartment of society" (Fischer-Kowalski 1997, 1998).

We propose to discern two autopoietic, self-regulated, interacting systems: society on the one hand, and nature on the other. We denote as "culture" the immaterial world of thoughts, beliefs, values, norms, communication, knowledge etc. (Popper's "world 3", see also Luhmann 1984), and as "nature" the material world (Figure 2). We may then postulate an interface between society, thought of as comprising culture and a material compartment which we call "physical compartment of society" (PCS) and nature. It seems appropriate to denote as "natural environment" the part of nature not included in the PCS. It appears plausible that any interaction between culture and nature needs some material agents. The most important agents are, of course, humans themselves which may thus, in this context, be regarded as part of the PCS.

Figure 2: A model for the interaction society – nature with reference to environmental indicators



Sources: Developed on the basis of Boyden (1992), Siefertle (1997a,b), Fischer-Kowalski (1997, 1998) together with M. Fischer-Kowalski, W. Bittermann, W. Hüttler, H. Weisz, H. Payer, F. Krausmann, C. Amann, K.H. Erb, and N. Schulz (*pers. comm.*, 1998)

If we accept this conceptual model, the difficult task remains to define its compartments. Defining the boundaries between the different compartments in Figure 2 is everything else but trivial. The boundaries should not be thought of as topographical but rather functional ones (Fischer-Kowalski et al. 1994, Fischer-Kowalski 1997, Winiwarter et al., *submitted*). It depends on the point of view which boundary is "visible". From the point of view of natural sciences it may be argued that, as humans are natural, all their artefacts are natural too, so the boundary between the PCS and the

natural environment becomes arbitrary. This, however, neglects that the structure and function of many "natural" entities, while being subject to the laws of nature as described by the natural sciences, would never have come into existence and function the way they do without human action, largely governed by cultural achievements. On the other hand, the boundary between the immaterial and the material world may appear quite straightforward to natural scientists, but it is difficult to separate "culture" from physical communication and information storage processes, i.e. separate the immaterial from the material compartment of society. We will elaborate on this question again further down after using the model for the construction of indicator systems.

3.2 Consequences for environmental indicators

For sustainability research the most important question is which socio-economic and natural dynamics drive environmental change. For environmental policy and for modeling the human dimension of Global Change, the focus will be on the human-induced part of the interaction. We may thus ask which socio-economic driving forces lead to pressures on the environment, which changes this will cause in natural systems, and how these changes will, in turn, impact on society. This impact will, however, concern the "physical compartment of society" (PCS) and may, in a second step, lead to a perception of environmental change. As trying to grasp the latter process with an indicator approach does not seem appropriate, we arrive at the following structure of an adequate indicator system (see Figure 2):

1. *Socio-economic driving forces*: Indicators for socio-economic dynamics that lead to pressures on the environment.
2. *Pressures on the environment*: Indicators for interaction processes between the PCS and its natural environment with potentially detrimental impacts on the environment.
3. *Natural states*: Indicators for the state of the environment. This may include indicators for natural processes and status variables describing the natural environment, but also certain physical stocks of society, as it is in many cases not possible to attach the label "societal" or "natural" to physical objects without referring to their function in a defined process. These indicators will focus on environmental changes caused by pressures.
4. *Impacts of environmental change on society*: Environmental change, regardless of its cause (natural or anthropogenic) may impact on society and must, therefore, be taken into account for the construction of a sufficiently complex environmental indicator system. This could also be termed "ecosystem services" (Hammond et al. 1995).

We believe that this classificatory scheme can resolve some of the fundamental problems associated with the PSR-scheme discussed in section 2.1. Instead of trying to specify criteria for social and economic sustainability – a task even more hampered by different ideological backgrounds than the definition of ecological sustainability criteria (Enquete-Kommission 1997) – we propose to operationalize the social, economic, and possibly institutional aspects of sustainability by including socio-economic driving forces and impacts of environmental change on society. (Of course it may be necessary to investigate into social and economic aspects of policy instruments employed to foster sustainable development, but this usually does not need new social and / or economic indicators.) The addition of "driving forces" to the OECD scheme reflects the recent discussions on environmental indicators which revealed that it is necessary to investigate into the causes why societies exert pressures on the environment (Hammond et al. 1995). The analysis of human driving forces for land use has also turned out to be an important part of land use and cover (LUCC) research (Lambin et al. 1998).

The reason why we do not include "response" indicators is that we doubt if this category is really useful in the context of sustainable development. First, responses include indicators for very different processes (e.g. measures to change driving forces or pressures as well as efforts to "repair" damaged ecosystems). Second, responses reflect an outdated paradigm of environmental policy, envisaging it as an additional policy field instead of as a fundamental principle for all relevant policy fields as for example social or economic policy. As sustainable development is often seen as an integrative concept, aiming at an integration of environmental policy into social and economic policy, the category "responses" does not adequately reflect the related information needs.

3.3 Basic Modes of Interaction: Metabolism and Colonization

It is now common to consider the relations between society and nature as a material and energetic input-output process in analogy to the biological metabolism of organisms. This physical exchange between societies and nature is widely called industrial, or more generally, socio-economic metabolism (Ayres and Simonis 1994, Fischer-Kowalski 1997, 1998). The concept of metabolism is currently increasingly used to construct material and energy flow analyses (Adriaanse et al. 1997, Ayres and Kneese 1969, Boulding 1973, Bringezu et al. 1997, Hüttler et al. 1997, Schandl 1998). The study of industrial metabolism is currently being established as core paradigm in the International Human Dimensions Programme on Global Environmental Change (IHDP) and is much debated in the fields of industrial ecology, ecological economics, and sustainable development (Meyer and Turner 1994, Erkmann 1997).

Industrial metabolism is an important concept of society-nature-interrelations and may be related to many environmental problems, e.g. resource scarcity, pollution, global warming etc. What may be even more important is that material and energy flows can be linked with socio-economic activities in a quite straightforward way. For example, in energy statistics it is usual to calculate the final energy consumption of economic sectors, and it is also possible to attribute losses in energy conversion from primary to final energy energy carriers. Material flow analyses are currently being improved with the aim of achieving a similarly detailed level of analysis. The establishment of physical input-output tables quite similar to the usual monetary input-output tables of the system of national accounts (SNA) is an important step in this direction.

An analysis of society-nature-interrelationships will, however, be incomplete if it relies solely on socio-economic metabolism. Besides extracting resources and discharging pollutants, societies also intervene into natural systems in order to render them more useful for some socio-economic purpose. Agriculture, for example, influences the species composition and nutrient availability on a defined area of land in order to produce certain kinds of biomass. We denote this type of society-nature interrelationship as "colonization of natural systems" and define it as the conundrum of social activities which deliberately change important parameters of natural systems and actively maintain them in a state different from the conditions that would prevail in the absence of human interventions. (Fischer-Kowalski and Haberl 1993, 1997, Fischer-Kowalski et al. 1997). Colonization may affect all kinds of natural systems, from biotopes to organisms (e.g. plant breeding) or genomes (e.g. genetic engineering). It creates systems in which some parameters are still self-regulated, but others are manipulated and regulated by society through the continuous application of work in a broad sense (i.e. human labor, animal labor, and work performed by machines).

An important part of colonization takes the form of land use, an important socio-economic driving force for the evolution of land cover patterns (Meyer and Turner 1994). Many human land use activities may be seen as colonization of the affected area's ecosystems. Colonization of ecosystems may affect a great variety of parameters, e.g. nutrient cycles, species composition, soil conditions, hydrologic features, and the energy flow.

4. Industrial metabolism and land use: Towards a common perspective

The connections between material and energy flows and land use are neglected in most work on industrial ecology or socio-economic metabolism. In its effort to establish material and energy flow accounts in close connection with economic statistics, this work tended to neglect the spatial dimension, i.e. the concrete areas needed to extract the materials, process them within society, and

hand them over to nature again. Land use research, on the other hand, focused on area needed and the analysis of spatial patterns, but did not, to our knowledge, establish an explicit link to material and energy flow analyses. We will here try to outline a common framework of analysis, drawing from empirical findings of our group for Austria.

4.1 Analyzing industrial metabolism

The study of socio-economic material flows has developed into a major field of interdisciplinary inquiry into the material (and energetic) interrelations between societies and their natural environment (Adriaanse et al. 1997, Hüttler et al. 1997, Schandl 1998). These studies show that the material turnover of industrial societies consists of about 95 % water and air and about 5 % of all other materials (fossil fuels, biomass, and mineral materials). The water throughput is certainly an important feature with respect to many environmental problems. Air input is generally not seen as an important environmental problem, but the output of exhausts certainly is. This, however, may be traced by concentrating on the throughput of other materials, and it is this aspect of socio-economic metabolisms that we turn to in the next paragraphs.

Studies of the last years reveal that we may employ the notion of a "characteristic metabolic profile" of industrial society. Table 1 reports empirical findings for five countries (Austria, Germany, Japan, the Netherlands, and the USA) for these "other materials". It shows that the per-capita material turnover is quite similar for all five countries if common definitions and calculation procedures are applied and, thus supporting the notion of a characteristic metabolic profile of the industrial mode of production of about $20 \text{ t.cap}^{-1}.\text{yr}^{-1}$. Mineral materials, mostly used for construction, account for nearly one half of the total throughput, most of it being added to the stock of buildings and transport infrastructure. Energy-rich materials, i.e. fossil fuels and biomass, are the other important parts of the throughput. This material flow is fueled by an energy flow of about 200 to 300 $\text{GJ.cap}^{-1}.\text{yr}^{-1}$, relying above all on fossil fuels, biomass, hydropower, and nuclear energy under modern industrial circumstances (Fischer-Kowalski and Haberl 1997).

Industrial metabolism is characterized by a high consumption level, compared to other modes of production (agriculture, hunter and gatherers). The material throughput of contemporary industrial societies is about 4 to 6 times higher than that of agricultural societies and Third World countries. The consumption level is strongly connected with the following three socio-economic activities (Schandl 1998): Construction accounted for more than 50 % of the total material throughput in Austria in the early 1990ies, energy supply (fossil fuels) was about 15 %, and nutrition for humans and livestock accounted for some 20 %.

Table 1: The characteristic metabolic profile of industrial societies: Domestic use of materials (i.e. domestic extraction plus imports minus exports) in 1991. The table only includes used materials, excludes air and water and "domestic hidden flows" (overburden, erosion and excavation materials) and the "ecological rucksacks of the imports".

	Austria	Japan	W.Germany (1990)	The Nether- lands	USA	unweighed arithmetic me- an
Biomass	5,6	1,4	3,3	10,2	3,1	4,7
oil, coal, gas	3,0	3,3	4,9	6,4	7,7	5,1
metals, minerals, others	11,2	11,7	10,5	6,4	8,9	9,7
total domestic consumption	19,8	16,4	18,5	22,4	19,7	19,5
(population in millions)	(7.8)	(124.8)	(63.2)	(15.0)	(252.3)	(5 countries)

Sources: Calculated from Adriaanse et al. (1997) and Schandl (1998)

Consumer goods play but a minor role, at least at the level of final consumption (they may be quite material intensive if we calculate all materials needed for their production in a "life-cycle" approach). Nevertheless, the overall dynamics of the material throughput of industrial societies is mainly related to the consumption of mineral resources like gravel, stone etc., fossil energy carriers, feedstuffs for livestock, timber, cement and one metal, namely iron (Schandl 1998).

While energy flows have been extensively studied (that is one reason why we did not elaborate on this issue here), the analysis of material flows is a quite newly emerging theme. The materials and energy flow approach leads to a variety of indicators on various temporal and spatial scales, e.g.:

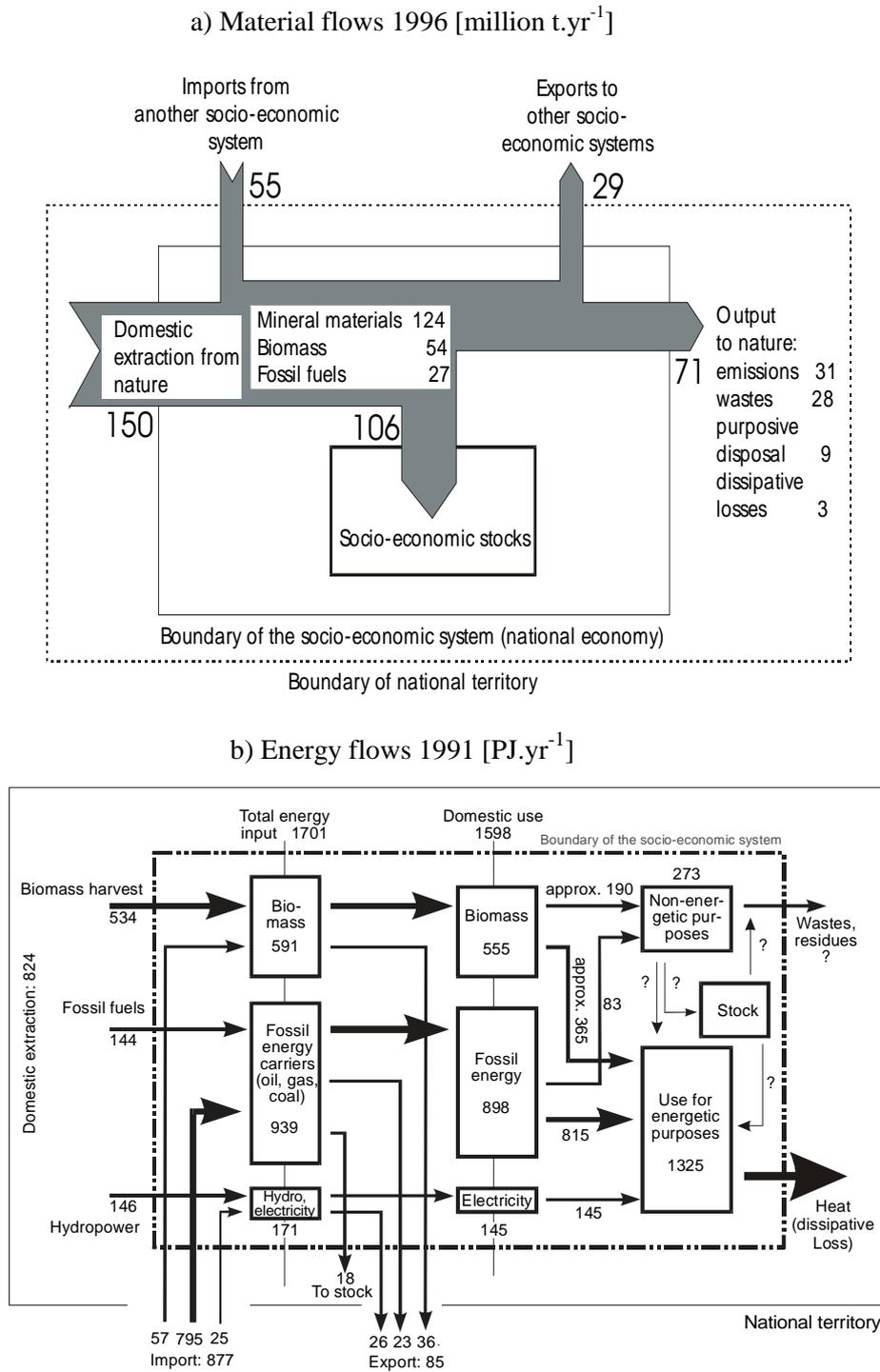
- Indicators for the total material throughput of the economy, e.g. *total material requirement* (which is the total amount of materials used to produce the goods and services consumed in an economy including material "rucksacks", i.e. the materials used to produce the imported goods, see Adriaanse et al. 1997), material flow indicators relying on the flow concept presented here, e.g. *total material input* (domestic extraction plus imports, measured as the weight crossing the border), *domestic consumption* (import plus domestic extraction minus exports). These two approaches are useful for different purposes: The first may be applied similar to Life Cycle Analyses (LCAs) and focuses on lowering the overall environmental burden of products (goods, services) (Schmidt-Bleek 1993, Hinterberger et al. 1994), the second is preferable for linking economic policy and environmental concerns and increasing the ecological efficiency of a national economy. Both approaches may also be used to calculate per capita values which is necessary for international comparisons.
- Material flow analyses may also be used below the national level. For example, they may be used to calculate the material input per service unit (MIPS), as proposed by Schmidt-Bleek

(1993). They may also be used to compare sectors of the national economy and relate the material input of a sector to its contribution to GNP (Schandl and Zangerl-Weisz 1997).

As these examples show, material (and, of course, energy) balances are a useful tool for relating monetary economic processes, as measured with economic indicators, with ecologically relevant properties of the economy. The investigation into the interrelations between the economy in monetary terms and the use of natural resources have been discussed since the late 1960ies by some economists (Daly 1968, Ayres and Kneese 1969, Leontief 1970). They used physical input output tables (PIOT) as a theoretical and empirical framework which satisfied the law of conservation of mass which is fundamental to the investigation of economic and environmental interrelations. The idea of PIOT again entered the discussion in recent years (Katterl and Kratena 1990, Fleissner et al. 1993, Schandl and Zangerl-Weisz 1997). Stahmer et al. (1997) provided a broad physical I-O for the German economy, closely related to the monetary I-O, but focusing on natural resources. Fischer-Kowalski et al. (1998) proposed a similar method called OMEN (Operating Matrix Economy Nature) in order to get consistent and internationally comparable material input/output balances from the incomplete, insufficient, and diverse statistical data which are used for national material flow analysis.

In Figure 3 we relate the material and energy flows in Austria 1996 to the national territory. Figure 3a shows that 73 % of the total material throughput of 205 million tons per year (Mt.yr^{-1}) is gained by domestic extraction, only about one quarter is imported. About 106 Mt.yr^{-1} is put on stock, mainly as built infrastructure (buildings, roads etc.). Outputs to nature are dominated by emissions and wastes. Purposive disposal is mostly fertilizer. Figure 3b shows the total energy flow of Austria 1991, including also usually neglected parts of the socio-economic energy flow as for instance the total amount of biomass used for nutrition and the wood used for so-called "non-energy" purposes (pulp and paper manufacture, furniture, construction etc.). It reveals that domestic extraction is less important for energy than for materials, as the import of fossil fuels plays a major role for energy supply. However, biomass is more important than usually accounted for in energy statistics. Although the "physical economy" appears to be connected to the national territory more than the economy in monetary terms, Figure 3 shows the extent to which modern means of transport have delinked the places where materials or energy are extracted, produced, consumed, and the off-products are discharged.

Figure 3: Socio-economic metabolism in Austria: Material and energy flow in the Austrian economy with reference to the national territory



Sources: a) IFF-Social Ecology and Austrian Central Statistical Office 1998
 b) Haberl 1997, Schulz 1998, Krausmann 1998

4.2 Metabolism and area use: A framework of analysis

Socio-economic metabolism and land use are closely linked processes. The material flows shown in Figure 3 need area mainly for two reasons: (1) Area is needed for the extraction of materials: Agriculture and forestry produce the required biomass, mining the fossil fuels and mineral materials extracted in Austria. And it is used for deposition of off-products, e.g. the areas needed for waste disposal. (2) The processing of the materials takes place within the built infrastructure: Primary materials are converted from raw materials to products in industrial buildings which are sold in commercial buildings, they are consumed in private buildings, and the wastes are treated in industrial plants before they are handed back to nature in one way or the other. Between all these places, raw materials and products have to be transported.

If we look at the energetic side of industrial metabolism, we encounter a similar picture: Energy is either gathered as some energy-rich material, e.g. biomass or fossil fuels. In this case the same logic applies. Or energy may be gathered in an immaterial form, e.g. as potential energy from rivers (it is a matter of debate if the water used in hydroelectric power generation should be included in the socio-economic metabolism), or as solar radiation or wind power. All these technologies use area, although in some cases there may be "area recycling" as in the case of solar collectors situated on the roof. The discharge of energy to the environment usually takes the form of low temperature heat as dissipative losses and thus usually does not need additional areas. However, in some cases area is needed even for this purpose, e.g. for cooling towers of nuclear or conventional thermal power plants.

An approach for connecting material flow analyses to land use could be to calculate the areas used for the steps of the socio-economic metabolism described above, i.e. the areas used for the extraction and discharge of materials, and the areas needed to host the infrastructure. Table 3 gives a first overview of the areas needed for the industrial metabolism in Austria.

Table 3 shows that the amount of material harnessed per unit area is about 2-3 orders of magnitude greater in the case of mining (minerals, fossil fuels) than in the case of biomass. The shift from an economy based above all upon biomass, as for example in hunter and gatherer and agricultural societies, to an economy based upon minerals and fossil fuels greatly reduces the amount of area needed per unit of throughput. This must be taken into account, for example, when sustainability problems of industrial and third world countries are compared.

Table 3: Area used for the industrial metabolism in Austria – preliminary data

a) Extraction / Deposition

	Area used [km ²]	Extracted materials [mio.t.yr ⁻¹]	Material flow / area [kg.m ² .yr ⁻¹]
Minerals, fossil fuels	234-1147	109	100-400
Crops	12.000-14.000	24,5	0,8
Grassland	15.400-18.400		
Forests	39.000-41.400	16,3	0,4
Deposition	No data	28	No data

b) Infrastructure

	Area used [km ²]
Built-up properties	2376
* Of this: sealed area (buildings)	384
Traffic infrastructure including "green areas"	2900
* Of this: area of traffic installations (94 % roads / parking, 3 % railroad, 2 % air traffic)	1422
* Of this: Sealed area	1300

Sources: Material Flow Analysis Austria 1996, BMWA, BMWV, Central Statistical Office Austria

Industrial metabolism and the extent of land use may thus, to some extent, be driven by the same socio-economic dynamics. The SPI and the Ecological Footprint Concept hint at exactly this point (Wackernagel and Rees 1995, Krotschek and Narodoslowsky 1996). Although the patterns of land use may be more affected by other factors than the amount of material throughput alone, material and, above all, energetic properties of socio-economic metabolism may be quite important for the extent as well as the spatial patterns of land use. For example, the use of fossil fuels that presumably was a precondition for the transition from the agricultural mode of production to the industrial one because it relieved the very narrow energetic limitations to agricultural societies (Smil 1992, Siefertle 1997b). These limits were essentially limits in available area, or, put the other way round, energetic limitations of transport processes: You can not transport (biomass) energy very far with a horse drawn carriage without using more (biomass) energy than may be stapled on it (Siefertle 1997b). These limitations severely constrained the development possibilities of agricultural land use patterns, e.g. urbanization, settlement patterns in general, distribution between different types of land use needed for food production and energy provision (forests) etc.

4.3 Colonizing landscapes: Appropriation of net primary production

A reason why material flow analyses and land use research have developed into quite distant research traditions may be that they relate to basically different types of society-nature interrelations: Material flow analyses rely on an input-output paradigm: Materials are extracted, converted, and discharged. In contrast, the ecosystems on an area used by society may be changed more or less

dramatically, but the area remains there. Area can not be used up, only the function of the area changes – for natural systems as well as for society. To use our notion: Landscapes, or ecosystems, are colonized by society. As discussed above, from the point of view of industrial metabolism, there are two main reasons for colonizing landscapes: (1) Extraction or discharge of materials, and (2) area used for infrastructure.

Land use studies usually use quite straightforward categories to characterize different types of land use, e.g. land used for crops, grasslands, built-up area etc. We claim that integrating land use and industrial metabolism will require to develop indicators that analyze the colonization of landscapes or ecosystems in a way which relates land use processes to the function they serve for society, and to the natural processes which are affected by them.

In what follows we will present an indicator which is able to do exactly this. This indicator, appropriation of net primary production (NPP), or, in short, NPP appropriation, analyzes the colonization of ecological energy flows by societies both through land use for infrastructure and through the various activities related to harnessing biomass as fuel and raw material, i.e. agriculture and forestry.

NPP is the biomass production of green plants on a defined area within one year, i.e. the amount of chemically stored energy produced by green plants through photosynthesis. NPP is the most widely used measure for the energy flow of ecosystems, because of the various parameters related to this it is most easily measurable. NPP is the main energetic basis of all food chains. Societies greatly influence the amount of NPP actually available for ecosystem processes on their territory:

- (1) They influence the productivity, i.e. the NPP per square meter and year of ecosystems, for example by constructing buildings, roads etc., and thus preventing NPP altogether, but also by agriculture and forestry, and
- (2) they harvest a significant proportion of the biomass which annually grows on their territory.

These two processes can be appraised with a single indicator called "appropriation of NPP" (Vitousek et al. 1986, Wright 1990, Haberl 1997) by defining NPP appropriation as the difference between the amount of NPP of the potential vegetation and the amount of energy available in ecosystems after harvest. Empirical studies show that the current level of NPP appropriation is significant. Vitousek et al. (1986) and Wright (1990) have estimated the world wide appropriation of NPP as 23 to 39 %.

In Table 4 we report values from an ongoing research project in which the appropriation of aboveground NPP in Austria was assessed in great detail (Haberl et al. 1998, Schulz 1998). The restriction to aboveground NPP (ANPP) was made, because data on subterranean NPP are quite uncertain, especially for forests. Table 4 shows that prevention of NPP through soil sealing and reduction of productivity of the vegetation compared to the potential vegetation through agriculture reduces the amount of NPP by 9-14 %. While the aboveground NPP of the potential Vegetation in Austria is about 1500 PJ.yr⁻¹, the actually prevailing vegetation only has a NPP of about 1290-1350 PJ.yr⁻¹. Socio-economic harvest takes another 545 PJ.yr⁻¹, so that only about 49-55 % of the initially yearly available biomass energy is still available for ecological processes in Austrias ecosystems.

Table 4: Socio-economic appropriation of aboveground net primary production (ANPP) in Austria around 1990

	Area [km ²]	ANPP of the potential (=undisturbed) vegetation [PJ.yr ⁻¹]	ANPP of the ac- tually prevailing vegetation [PJ.yr ⁻¹]	Socio- economic harvest of ANPP [PJ.yr ⁻¹]	ANPP ap- propriation [PJ/yr ⁻¹]	ANPP appro- priation [% of poten- tial ANPP]
Urban area ¹	1500-2350	30-50	10-20	1	20-40	60-75%
Arable land ²	12.000-14.000	250-290	225-250	220-235	245-275	95-98%
Pastures ³	15.400-18.400	310-370	220-280	115-132	205-225	60-70%
Forests	39.000-41.400	730-780	730-780	188	188	23-26%
Natural areas ⁴	10.900-12.400	50-65	50-65	3	3	5-6%
Austria total ⁵	83 000	1480-1500	1290-1350	545	680-750	45-51%

¹ built-up area, industrial areas, traffic zones, mining etc. (including parks, urban lawns etc.)

² including vineyards

³ and other heterogenous agricultural areas

⁴ alpine vegetation, glaciers, wetlands etc. (including alpine pastures)

⁵ excluding inland water

Source: Calculated on the basis of Haberl et al. (1998). This study included three different sets of data on land use and cover based on remote sensing, GIS modeling, and statistical data sources. Numbers have been rounded .

Table 5 analyzes NPP appropriation by sector. It shows that agriculture accounts for nearly three quarters of NPP appropriation, while soil sealing through infrastructure still is a minor factor in Austria. On smaller regional scales, e.g. in urban areas, this is quite different: Here infrastructure may cover quite significant parts of the area. The prevention of ANPP contributes 19-28 % to the ANPP appropriation, most of which is caused by agriculture. This indicates that, despite high yields, agricultural areas are less productive than the natural vegetation they replace (e.g. wheat fields are less productive than pristine forests). Soil sealing only contributes some 3 to 5 % to ANPP appropriation, agriculture some 70 to 75 %, logging 25 to 28 %.

It is highly likely that values for ANPP appropriation in many other European countries are even higher than in Austria. Most European countries have less than the Austrian 45 % of forests with

rather low NPP appropriation per unit area. Furthermore, about 13 % of the Austrian territory are above 1800 m elevation where no NPP appropriation can be assumed to occur. Additionally, in other countries, agricultural areas, roads and buildings are likely to cover a higher percentage of the surface.

Table 5: Socio-economic appropriation of above-ground net primary production (ANPP) in Austria – breakdown by sectors

	Prevention of NPP ¹ [PJ.yr ⁻¹]	Harvest [PJ.yr ⁻¹]	Total [PJ.yr ⁻¹]	Total [%]
Built-up area ²	20-40	1	21-41	3-5 %
Agriculture	110-190	373	483-563	70-75 %
Forestry	-	190	190	25-28 %
Total	130-210	563	690-750	100 %
Total [%]	19-28 %	72-81 %	100 %	

¹ Reduction of productivity (NPP per unit area) through land use activities

² buildings, traffic zones, industrial areas etc.

Source: Calculated on the basis of Haberl et al. 1998, Krausmann 1998, and Schulz 1998

NPP appropriation is highly relevant for several ecosystem processes. It alters the quantity of energy available for ecosystem processes (food chains), and it changes the quality of the available biomass: While in forests 50 to 65 % of the aboveground NPP (ANPP) is allocated to woody parts, nearly all ANPP is allocated to herbaceous parts in pastures and fields. NPP appropriation is associated with a significant reduction of the standing crop of ecosystems, i.e. the biomass stock of live vegetation. According to calculations of Erb (*pers.comm.*), various land use activities have reduced the standing crop in Austria by some 74 %. While the standing crop of the potential vegetation in Austria totaled about $2.2 \cdot 10^9$ tons (Gt) dry matter, the corresponding value for the actual vegetation is about 0.8 Gt. The difference of about 1.4 Gt equals about $640 \cdot 10^6$ tons (Mt) carbon which had been released during the past few thousand years when the Austrian territory was colonized, resulting in the current land use and cover patterns. For comparison, we may note that the annual CO₂ emissions in Austria from fossil fuel combustion amount to about 16 Mt of carbon. This implies that biomass use only may be regarded as CO₂ neutral if current land use patterns are taken as given. Increasing biomass use by converting pristine forests to managed forests or agricultural areas will, however, result in quite significant net CO₂ releases.

There is also evidence that NPP appropriation, in lowering the energy available for heterotrophic food chains, may have a negative impact on the average length of food chains and, consequently, on biodiversity. There is, however, still a lot of discussion to this point. While it is clear that the harvest of anything near 100 % of the NPP would leave no energy for all wildlife species which in turn would result in the extinction of most heterotrophic organisms as for example animals and

fungi, it remains a matter of debate, however, what effects may be expected at levels of NPP appropriation significantly smaller than 100 % on higher spatial levels of landscapes with a diverse pattern of different types of land cover and use.

NPP appropriation encompasses domestic biomass extraction, i.e. a material flow indicator, together with a variety of different land uses. It may be related to economic activities (soil sealing through construction, agriculture, and forestry). It integrates various land use activities into one parameter which may be assessed on nearly every spatial level (from a GIS grid cell for which land use and cover data may be assessed to any political spatial level (municipalities, districts, provinces, national totals etc.). It is connected with indicators for natural states, e.g. the standing crop of ecosystems, and processes (e.g. the net primary production of the actual vegetation).

NPP appropriation directly impacts on biogeochemical flows and processes. A similar measure has been used to assess land use-related encroachment of tropical rain forests (Jang et al. 1996). As NPP appropriation impacts on carbon exchange rates, it may also be an interesting, currently neglected (e.g. Schimel 1995), approach for Global Change research.

5. Conclusions

We believe that it is useful to conceptualize sustainable development as an interaction process between societies and their natural environment. The following processes and states of this interaction may be monitored with appropriate indicator systems: Immaterial socio-economic dynamics, usually denoted as *socio-economic driving forces*, leading to material exchanges between a physical compartment of society and its natural environment which may be, insofar as they are potentially detrimental, denoted as *"environmental pressures"*. These, in return may change structures and processes within natural systems which may be monitored with *"state indicators"*. If we seek to develop indicator systems which are able to be used for sustainability policy, we must also develop indicators for *impacts of environmental change on society*. Of course, these impacts will lead to a perception of environmental change in the (immaterial) cultural system, but this is beyond the realm of environmental indicators. (The whole indicator system may be viewed as a tool for this perception process.) An indicator system based upon this model may be able to overcome the shortcomings of the currently used "pressure-state-response" scheme, which was not successful in guiding the development of a comprehensive system of sustainability indicators so far. Such a system could incorporate all relevant, and successful, efforts carried out so far on pressure and state indicators and current work on driving forces. It will be no big problem if it will not be able to include the mostly unsatisfactory attempts for response indicators.

There currently are considerable research gaps for putting the big current scientific questions in the field of human dimensions of environmental change, i.e. industrial metabolism and land use and cover change, in a common perspective. We believe that the notion of "colonization of nature", i.e. the purposive societal intervention into natural systems with the aim of "improving" them with respect to socio-economic goals, may serve as theoretical as well as an analytical tool in this field. We have demonstrated that this notion is able to guide the development of indicators which are able to link material and energy flows to land use processes in a theoretically plausible as well as empirically observable manner. These indicators may be linked to socio-economic driving forces, e.g. to economic indicator systems, but they may as well be observed on nearly every spatial level, from GIS grid cells to the national level and are closely connected to land use and cover patterns. An important strategy in this field may be to relate land use to its function for socio-economic metabolism as well as to the interventions into natural processes related to different types of land use. The notion of colonization could be an appropriate approach to guide such efforts.

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