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Socio-ecological indicators for sustainability

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Abstract

A systematic framework of indicators for sustainability is presented. In our approach there is an emphasis on societal activities that affect nature and on the internal societal resource use, as opposed to environmental quality indicators. In this way the indicators may give a warning signal to an unsustainable use of resources early in the chain from causes in societal activities to environmental effects. The aim is that these *socio-ecological indicators* shall serve as a tool in planning and decision-making processes at various administrative levels in society. The formulation of the indicators is made with respect to four principles of sustainability, which lead to four complementary sets of indicators. The first deals with the societal use of lithospheric material. The second deals with emissions of compounds produced in society. The third set of indicators concerns societal manipulation of nature and the long-term productivity of ecosystems. Finally, the fourth set deals with the efficiency of the internal societal resource use, which includes indicators for a just distribution of resources.

Keywords: Indicators; Sustainability

1. Introduction

The publication of the Brundlandt report 'Our Common Future' (WCED, 1987) and the Rio Declaration (United Nations, 1992a) put the challenge of sustainable development on the agenda for planners, decision makers and politicians at all administrative and institutional levels of the global society. Since then, much effort has been made to define and operationalise the concept of sustainability.

Many researchers have suggested various types of non-monetary measures to indicate to what extent environmental states and functions, material flows, or societal activities can be regarded as sustainable (see, e.g., Vos et al., 1985; Liverman et al., 1988; Kuik and Verbruggen, 1991; Opschoor and Reijnders, 1991; Holmberg and Karlsson, 1992; Adriaanse, 1993; Alfsen and Sæbø, 1993; Bergström, 1993; Gilbert and Feenstra, 1994; Moffatt, 1994; OECD, 1994). Most sets of indicators developed so far have focused on the state of the environment rather than on the relation between society and ecosystems. In the present paper we formulate indicators based on four socio-ecological principles for sustainability (Holmberg et al., 1996). The principles

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and, hence, the indicators focus early in the *causal chain*—i.e., in the chain of causes in society to effects in the environment. In this way socio-ecological indicators may give an earlier warning than would environmental quality indicators.

There are two aspects that are important in the construction of our indicators:

(i) There are in many cases long time delays between a specific activity and the corresponding environmental damage. This means that indicators based on the environmental state may give a warning too late, and in many cases only indicate whether past societal activities were sustainable or not.

(ii) The complexity of the ecosystems makes it impossible to predict all possible effects of a certain societal activity. Some damages are well-known, but others have not yet been identified. Most of the sustainability indicators suggested so far are formulated with respect to known effects in the environment. We suggest that indicators of sustainability should be formulated with respect to general principles or conditions of sustainability.

The socio-ecological principles that form the basis of the socio-ecological indicators focus on the societal activities and interactions with nature and internal societal resource use. The first principle deals with societal use of elements from the lithosphere. The second principle deals with the necessary restrictions on emissions of anthropogenically produced substances. The third principle concerns the anthropogenic manipulation of nature. Finally, the fourth principle deals with the efficiency of the societal resource use. These principles have in common that they are formulated in terms of societal activities.

We use these four principles as a systematic framework for developing indicators. Our aim is then to define indicators that are based on data that reflect societal activities rather than the state of the environment. In the present paper we exemplify the four different types of indicators by calculating their values using mainly global data.

In Section 2, we discuss various approaches that have been made to indicate sustainability. In Section 3, the four socio-ecological principles for sustainability are reviewed. Then, in Section 4, we develop a set of indicators for each of the four principles. Numerical estimates of these indicators are also presented. Section 5 is devoted to a discussion of the results and on areas for future research.

2. Indicators for sustainability

There are both monetary and physical approaches to indicating sustainability. In this paper we focus on physical indicators. Such indicators can be divided into three (main) groups: (i) societal activity indicators (that indicate activities occurring within society—the use of extracted minerals, the production of toxic chemicals, recycling of material), (ii) environmental pressure indicators (that indicate human activities that will directly influence the state of the environment—e.g., emission rates of toxic substances) and (iii) indicators of the state of the environment or environmental quality indicators (that indicate the state of the environment—e.g., the concentration of heavy metals in soils and pH levels in lakes).

It should be noted that most indicators for sustainability developed and used so far belong either to the group of environmental pressure indicators or to the state of the environment indicators. This is shown in Table 1 where we have illustrated where some authors have put their focus when developing and evaluating indicators for sustainability.

3. Principles of sustainability

In our formulation of indicators for sustainability we use a framework of principles that should be fulfilled in a sustainable society (see Holmberg et al., 1996). The principles are presented below.

Table 1
The focus of some indicators for sustainability

Reference	Indicated area	Societal activities	Environmental pressure	State of the environment
Adriaanse (1993)	The Netherlands	x	x	
Alfsen and Sæbø (1993)	Norway			x
Ayres (1995)	Mainly USA	x	x	
ten Brink (1991)	Specific ecosystem			x
Brown et al. (1994)	The world	x	(x)	(x)
Carlson (1994)	Sweden	x	x	
ECE (1985)	ECE member countries	(x)	x	x
Environment Canada (1991)	Canada		x	x
Gilbert and Feenstra (1994)	Specific ecosystem		(x)	x
Holdren (1990)	The world		x	(x)
Holmberg and Karlsson (1992)	Not specific	x	x	
Miljøministeriet (1991)	Denmark	(x)	x	x
Nilsson and Bergström (1995)	Municipality and company	x	x	x
OECD (1994)	OECD countries	(x)	x	(x)
Opschoor and Reijnders (1991)	Not specific		x	x
SNV (1994)	Sweden			x
Haes et al. (1991)	Specific ecosystem			x
Vos et al. (1985)	The Netherlands		x	x
This paper	The world	x	x	

The symbol 'x' indicates the main focus of the work, while (x) means that such indicators are included, but only play a minor role in the work.

3.1. Principle 1: substances extracted from the lithosphere must not systematically accumulate in the ecosphere.

Elements from the lithosphere must not be spread at a rate which will give rise to a systematic increase in the ecosphere. Such an increase will occur if the sum of the anthropogenic emissions and the natural flows from the lithosphere to the ecosphere (weathering processes and volcanic eruptions) exceeds the sedimentation rate and the rate of final disposal in the lithosphere. Because of the complexity and delay mechanisms of processes in the ecosphere, it is extremely hard to say what level of accumulation will cause an effect. In fact, every substance has a limit (often unknown), above which damage occurs in the ecosphere. Increasing amounts of carbon dioxide in the atmosphere, of sulphur dioxide leading to acid rain, of phosphorus in lakes and of heavy metals in soils and in our bodies are all examples of such accumulation. In practice, this principle implies restrictions on the extraction rate of metals and fossil fuels in combination with increased recycling of material and decreased dissipative use of scarce elements. It also implies substitution of abundant elements for scarce elements.

3.2. Principle 2: society-produced substances must not systematically accumulate in the ecosphere.

In the technosphere, molecules and atomic nuclei of different kinds are produced, some of them long-lived, in amounts previously unknown to the ecosphere. If they are emitted faster than they are degraded into molecules or nuclides that can be integrated in the ecospheric cycles, and/or faster than they are removed to the lithosphere, such substances will accumulate in the ecosphere. In order to reduce the amount emitted, one can degrade substances within the technosphere or deposit them in final disposals. CFC molecules destroying the ozone layer, increasing amounts of DDT and PCB in biota, and radioactive inert gases in the atmosphere are all examples of such accumulation. The principle also implies that persistence is a very important aspect of substances that are foreign to nature, and therefore there should be strong restrictions on the use of persistent substances foreign to nature.

Finally, we note that higher concentrations in the ecosphere may lead to increased sedimentation rates (for Principles 1 and 2) and/or higher degradation rates (for Principle 2) so that a new equilibrium concentration may be established.

3.3. Principle 3: the physical conditions for production and diversity within the ecosphere must not become systematically deteriorated.

A sustainable society must not systematically reduce the physical conditions for the long-term production capacity in the ecosphere or the diversity of the biosphere. Society must neither take more resources from the ecosphere than are regenerated nor systematically reduce natural productivity or diversity by manipulating natural systems. Deforestation, soil erosion, land degradation with desertification as an extreme form, extinction of species of plants or animals, exploitation of productive land for asphalt roads and refuse dumps, and destruction of freshwater supplies are examples of such reduction.

Society is dependent on the long-term functions of the ecosystems. Even if Principle 1 and Principle 2 are fulfilled, society must be careful with its manipulation of the resource base in order to avoid a loss of the productive capacity for the supply of food, raw materials and fuel. This dependence will become more obvious when the use of fossil fuels is reduced (in accordance with Principle 1).

3.4. Principle 4: the use of resources must be efficient and just with respect to meeting human needs.

Principles 1, 2 and 3 constitute the external conditions for a sustainable metabolism of a society. The assimilative capacity as well as the available resource flows are limited. In order to fulfil human needs for a growing global population, the resources and services obtained from nature must be used efficiently within the society. Socially, efficiency means that resources should be used where they are needed most. This also leads to the requirement of a just distribution of resources among human societies and human beings.

4. Socio-ecological indicators for sustainability

For each of the socio-ecological *principles* reviewed in the previous section we define a set of socio-ecological *indicators*. These indicators are formulated so that they reflect to what extent (a certain aspect of) a societal activity violates the corresponding principle.

4.1. Indicators for Principle 1

The basic idea behind the first principle is that the total flow of an element from the lithosphere to the ecosphere—i.e., societal emissions of an element extracted from the lithosphere as well as weathering and volcanic processes, should not exceed the return flow of the same element from the ecosphere to the lithosphere, by sedimentation processes and by flows to final deposits in the lithosphere.

As a starting point for the formulation of indicators for Principle 1, we use Fig. 1, which shows some basic features of the cycle of a specific element between the lithosphere, the technosphere and the ecosphere.

The variables used are X_T and X_E for the total contents of the element in the technosphere and the ecosphere, respectively, and X_R for the total resources. Furthermore, k_{ex} is the annual rate of extraction, k_w is the total natural contribution to ecosphere (i.e., weathering and volcanic eruptions), k_{em} represents the emissions of the element from the technosphere and k_s is the rate of sedimentation from the ecosphere to the lithosphere. It should be observed that in general k_s is an increasing function of the total content in the ecosphere.

Society can prevent the accumulation of lithospheric materials in the ecosphere by (i) limiting the extraction rate, (ii) limiting the leakage from the technosphere—i.e., by using high degree of recycling and by avoiding

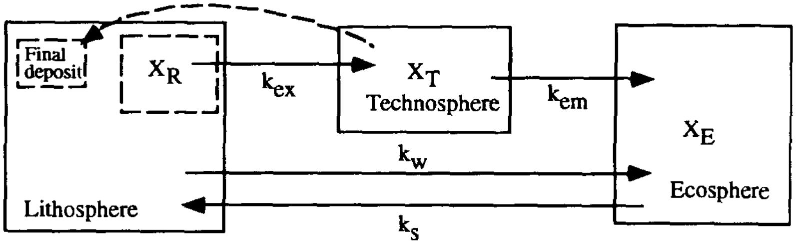

Fig. 1. An element is extracted from the lithosphere and used in the technosphere. Eventually it will be emitted to the ecosphere, where it will remain until sedimentation processes once again bury it in the lithosphere. The figure shows that the total contents of the element will increase in the ecosphere if the total emissions from the technosphere (k_{em}) plus the natural flow from the lithosphere (k_w) exceed the rate of sedimentation (k_S). The dashed line represents direct flows from the technosphere to the lithosphere for final deposition in repositories. At present, this option is only planned for radioactive waste.

dissipative use, (iii) returning the material to underground repositories (dashed line in Fig. 1) and (iv) increasing the sedimentation rate (e.g., by guiding the emissions from the technosphere to areas in the ecosphere where the sedimentation rate is high).

There are several reasons for putting the focus early in the causal chain when indicating Principle 1. The elements that are extracted do not disappear and as long as we do not have clever strategies for preventing accumulation in the ecosphere, a plausible first approximation is therefore that the elements extracted will eventually leak to the ecosphere. Furthermore, the diffuse emissions from the consumption sector of the economy now exceed the more easily detected emissions from the production sector for many elements. Bergbäck (1992) has shown that this is the case for many metals used in Sweden. The residential time is often longer in the consumption sector than in the production sector.

4.1.1. Indicator no. 1,1: lithospheric extraction rates

If the rate of extraction is high compared to the natural sedimentation process, accumulation will occur in the technosphere, and sooner or later in the ecosphere. The material accumulated in the technosphere will eventually leak to the ecosphere. Thus, it is important to indicate the extraction rate of each element. We define the first indicator $I_{1,1}$ for Principle 1 as the extraction rate divided by the rate of natural supply [1] from the lithosphere to the ecosphere by weathering and volcanic eruptions, i.e.:

$$I_{1,1} = \frac{k_{ex}}{k_w}, \tag{4.1}$$

where we use the convention that the first digit in the subscript of I refers to the principle and the second is an index for the different indicators within this group. This first indicator, the *Lithospheric Extraction Indicator (LEI)*, has the advantage that it is straightforward and easy to understand, and that data are relatively easy to obtain. This type of indicator has been proposed as a measure of anthropogenic disruption of natural cycles by Benjamin and Honeyman (1992). If $I_{1,1} = 1$, the present anthropogenic extraction is equal to the natural supply to the ecosphere. This implies that anthropogenic perturbations of the natural biogeochemical cycles are considerable and we can expect significant changes in the concentration of the element in question in the ecosphere.

According to Principle 1, sustainability requires that the concentration of each of the elements must not increase systematically in the ecosphere. One could say that anthropogenic perturbations of the natural

[1] The natural supply to the ecosphere is balanced by the natural sedimentation back to the lithosphere.

biogeochemical cycles must be small, which implies values of $I_{1,1}$ (much) less than unity. This should be viewed as a rule of thumb, and in specific cases one may argue for more exact acceptable values for this indicator. Even if there is no obvious critical value for the indicator, one can make a first comparison by looking at the order of magnitude of the indicator for different elements. In this way one can get an indication of, for instance, which metals could possibly substitute for others. If we focus on the use of a specific element, the indicator should be calculated for a time series to reveal the trend towards or away from sustainability.

4.1.2. Indicator no. 1,2: accumulated lithospheric extraction

It is also of interest to indicate the accumulated amount of a specific element in the technosphere in relation to the ecospheric content of that element. We are especially interested in the total pre-industrial content in the human area soils, [2] which we denote by X'_E and we define:

$$I_{1,2} = \frac{1}{X_{E'}} \int_{-\infty}^{0} k_{ex}(t)\,dt = \frac{X_{A'}}{X_{E'}}, \tag{4.2}$$

where X_A is the accumulated extraction from the lithosphere. For many metals most of the mining has been carried out during this century and most of the extracted amount still remains in the technosphere. In this case the indicator can be approximately written $I_{1,2} \approx X_T/X'_E$, where X_T is the amount in the technosphere.

We refer to this ratio as the *Accumulated Extraction Indicator.* [3] The indicator $I_{1,2}$ can be used as an early warning signal. If its value is high, then there are reasons for analysing the flows of that element in more detail (e.g., by comparing flows in natural sedimentation processes with the leakage from the technosphere) and possibly considering final deposit of the element. Cadmium has been discussed in this context by van der Voet and Kleijn (1992).

4.1.3. Indicator no. 1,3: non-renewable energy supply

Several environmental problems are related to the use of non-renewable energy. Hence, we have chosen to indicate the ratio between non-renewable energy and total primary energy supply.

$$I_{1,3} = \frac{\text{Non-renewable primary energy supply}}{\text{Total primary energy supply}}. \tag{4.3}$$

In Fig. 2, we present a time series for this indicator.

4.1.4. Other indicators

There are also other indicators that can be formulated from the variables of Fig. 1, Fig. and Fig. , and that reflect important aspects of societal resource use (e.g., k_{em}/k_w or indicators for emissions to specific parts of the ecosphere), such as anthropogenic emissions of metals to the atmosphere, aquatic systems and soils (Lantzy and Mackenzie, 1979; Nriagu and Pacyna, 1988).

The efficiency in the use of elements within society (e.g., the degree of recycling) is dealt with in connection with Principle 4. Also, indicators focusing on the problem of the limited amount of lithospheric resources belong to Principle 4 since they deal with intergenerational justice.

It has been argued that for most elements the assimilation capacity of the ecosphere is a more restrictive constraint on the use of these elements than the amount of the resources available in the lithosphere (see, e.g., Holmberg et al., 1996). A possible exception may be phosphorus, which is a non-substitutable macro-nutrient.

[2] The human area is the top soil layer (to 0.2 m depth) of land used for the technosphere. Vitousek et al. (1986) call this the 'human area' and assign it a value of 2 million km^2. It is possible to choose a different reference area, but it will not affect the comparison between different substances in any significant way.

[3] Wallgren (1992) has called this ratio the *Future Contamination Index (FCI)* when calculating its value for some metals used in Sweden.

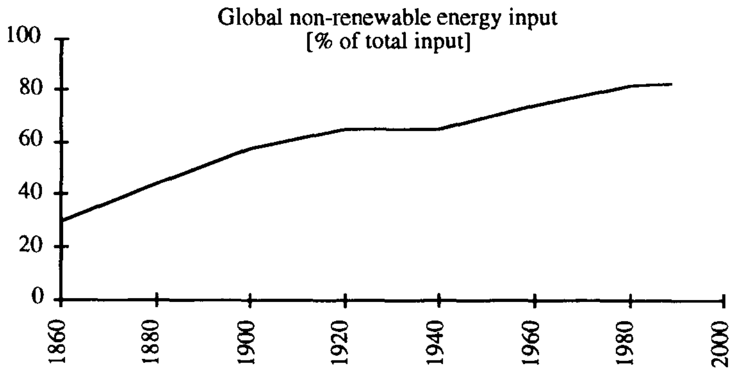

Fig. 2. The ratio between non-renewable energy and total energy supply. Data based on BP Statistical Review.

4.1.5. Numerical examples

In Table 2 the indicators $I_{1,1}$ and $I_{1,2}$ are given for some of the elements that are extracted from the lithosphere.

If we look at $I_{1,1}$, in Table 2, we see that for many elements the anthropogenic flows dominate over the natural flows. The discussion of the environmental implications for metals such as Pb, Hg and Cd has already begun. But we see from the table that this discussion must soon include other elements as well (e.g., Cu, which has even higher values for the indicator $I_{1,1}$). A plausible reason why the use of Cu is not yet discussed can be that this metal has a longer residence time within society and that we have traditionally put our focus on effects in nature. A high degree of recirculation of elements within society and careful handling of the elements (non-dissipative use) can reduce the risks associated with high values for the indicator.

Note that $I_{1,1}$ indicates a flow while $I_{1,2}$ indicates a state. A high value of $I_{1,1}$ and a low value of $I_{1,2}$ is a warning that a rapid accumulation is taking place and $I_{1,2}$ will increase. Therefore, $I_{1,1}$ lies earlier than $I_{1,2}$ in the causal chain.

The values for the indicator $I_{1,1}$ for the elements C, S and P are considerably larger than unity (see Table 2). The environmental effects that are known from the emissions of these elements—the greenhouse effect, acidification and eutrophication—clearly show that in all three cases we have exceeded a critical value for this indicator.

4.2. Socio-ecological indicators based on Principle 2

According to the second socio-ecological principle for sustainability, substances that are produced in society must not systematically accumulate in the ecosphere. Here, we formulate socio-ecological indicators for substances that are naturally existing (Section 4.2.1) and for substances that are foreign to nature (Section 4.2.2).

4.2.1. Indicators for man-made substances that are naturally existing

The main idea behind the two first principles for a sustainable society is that sustainability requires that human disruption of the natural cycles and flows of substances are small enough to avoid a systematic accumulation.

4.2.1.1. Indicator no. 2,1: anthropogenic flows compared to natural flows. As the first indicator for substances that are naturally occurring, we suggest the ratio:

$$I_{2,1} = \frac{E_a}{E_n}. \tag{4.4}$$

Table 2
Indicators for elements extracted from the lithosphere

Element	Conc. in soils (mg/kg)	Weathering [a] and volcanic (kton)	Mining (kton)	Fossil fuels [b] (kton)	$I_{1,1}$ [c]	$I_{1,2}$ [d]
Metals						
Al	72000	1100000	18000	34000	0.048	0.01
Fe	26000	390000	540000	34000	1.4	1
K	15000	230000	24000	340	0.11	
Mg	9000	140000	3100	690	0.028	0.01
Ti	2900	44000	2500	1700	0.096	0.02
Mn	550	8300	8600	170	1.1	
Zr	230	3500	880	140	0.3	
V	80	1200	32	350	0.32	
Zn	60	910	7300	260	8.3	6.9
Cr	54	830	3800	34	4.6	2.6
Cu	25	380	9000	55	24	23
Li	24	360	9.9	220	0.64	
Ni	19	300	880	570	4.8	2
Pb	19	290	3300	85	12	19
Ga	17	260	0.037	24	0.092	
Nb	11	170	14	14	0.17	
U	2.7	41	47	3.4	1.2	
Sn	1.3	20	210	5.7	11	
Mo	0.97	15	110	17	8.5	4.2
Be	0.92	14	0.34	10	0.76	
Cd	0.35	5.3	20	3.4	3.9	3
Hg	0.09	1.4	5.2	10	6.5	17
Ag	0.05	0.75	15	1.7	22	
Semi-metals						
Si	310000	4700000	4600	95000	0.021	
B	33	500	0.37	250	0.52	
As	7.2	110	19	18	0.33	
Ge	1.2	18	0.27	17	0.96	
Sb	0.66	9.9	54	10	6	
Non-metals						
C	25000	780000		5400000	6.4	
S	1600	33000	58000	100000	3.7	
F	950	14000	2300	240	0.17	
P	430	6500	21000	1700	3.5	
Se	0.39	5.9	2.1	12	2	

[a] Weathering mobilization is calculated using average concentration in soils (column 1) and suspended sediment flux of $1.5 \cdot 10^{16}$ g per year in rivers (Nriagu, 1990).
[b] Data for contents of trace elements in crude oil are from USA (Yen, 1975). However, the only elements for which flow associated with crude oil are considerable compared with the flow associated with coal are V, Ni and Hg. The flows of elements associated with fossil fuels predominate over the amount that is mined for several elements: e.g., V, Li, Ga, Be, Hg, Si, B, Ge, S, Se and, of course, for C. Surprisingly, this is also true for aluminium.
[c] Indicator $I_{1,1}$ is calculated as anthropogenic flows from the lithosphere to the ecosphere divided by the natural flows. The anthropogenic flows are mining and flows associated with fossil fuels and the natural flows are weathering and volcanic processes. Data from 1990.
[d] Indicator $I_{1,2}$ is calculated as the accumulated mining since 1900 divided by the amount in the top soil layer in the human area (see the text). If flows from fossil fuels had been included, the indicator value would increase substantially for a number of elements.
Source: BP Statistical Review, Yen (1975), Valković (1983), Nriagu (1989), Sposito (1989), Crowson (1992), Speight (1992), Wallgren (1992), Walker and Kastings (1992), Sigenthaler and Sarmiento (1993), Holmberg et al. (1996) and Karlsson et al. (1994).

Table 3
Indicators for Principle 2

Substance	$I_{2,1}$	$I_{2,2}$
CO_2	0.07	1.8 [a,b]
CH_4	1.4–4.1	2.7 [b]
$N_2(g) \rightarrow N(active)$	1.3–3	–
N_2O	0.5–1	1.5 [b]
NH_3 and NH_4^+	0.02–0.09	–
NO_x	1.9–2.6	–
SO_2	0.7–6	
C^{14}	0.1	1.1

[a] The value for the second indicator for CO_2 gives the atmospheric concentration in the year 2100 divided by the pre-industrial concentration, given that the present global emissions are kept constant. In order to estimate the long-term atmospheric concentration of CO_2, one has to make assumptions about emissions scenarios and fossil fuels reserves. Maier-Reimer and Hasselman (1987) estimate that for a stock of fossil fuels equal to 5000 Gton C, the atmospheric concentration of CO_2 would reach peak concentration as high as 4.5–6.4 times the pre-industrial level (all depending on the rate at which the stock of fossil fuels is combusted). No net-sink in biomass is assumed.
[b] Values from IPCC (1995).
Sources: Bolin (1979), Söderlund and Rosswall (1982), IPCC (1990), IPCC (1992), IPCC (1995), Jaffe (1992), Bates et al. (1992), Graedel and Crutzen (1993), UNSCEAR (1993).

Here E_a is the anthropogenic rate of production of a given substance and E_n is the natural rate of production. This indicator is analogue to indicator $I_{1,1}$ (see Eq. 4.1).

4.2.1.2. Indicator no. 2,2: the long-term implications of present emissions. It is not clear from the value of indicator $I_{2,1}$, what the long-term content will be in the ecosphere. An analysis of the long-term content requires specific models of how, where and when the substance is released to the ecosphere. In some cases, however, this is easily done. For some substances that are released to the atmosphere, and whose life-times are long enough to guarantee a relatively homogenous distribution throughout the atmosphere, a simple model can be used in order to get a rough picture of the total content $M(t)$ of the substance in the atmosphere at time t. The time derivative of $M(t)$ is given by:

$$\dot{M}(t) = E_a + E_n - kM(t), \tag{4.5}$$

where k is the rate of degradation (or removal) from the atmosphere. Whenever this formula is applicable, it is straightforward to evaluate the long-term stationary atmospheric content for the present rate of emissions divided by the pre-industrial atmospheric content, M_{preind}. This ratio is our second indicator for Principle 2, and it is given by:

$$I_{2,2} = \frac{E_a + E_n}{kM_{\text{preind}}} = 1 + \frac{E_a}{E_n}. \tag{4.6}$$

In Table 3, we present values for the indicators $I_{2,1}$ and $I_{2,2}$ for some common substances. If $I_{2,1} = 1$, then the anthropogenic flows equal natural rates of production, which implies a considerable disruption of the natural cycle of that substance. The implication of the indicator value $I_{2,1} = 1$ is in general not clear due to uncertainties about the decay processes for different substances. This is, however, not the case for those substances that can be described by Eq. 4.5. For these substances, the long-term atmospheric concentrations will increase by a factor of two (which is easily seen in Eq. 4.6).

It should be noted that also rather small values for the indicator $I_{2,1}$ could be unsustainable. Consider, for instance, emissions of CO_2. Anthropogenic emissions amount to 7.1 ± 1.1 Gton C/year (IPCC, 1995). But at the same time, respiration by biota gives rise to an annual production of 100 Gton C. Thus, we have $I_{2,1} = 0.07$, which may appear rather small. But since CO_2 is a stable compound, the present rate of emission will cause a systematic increase in the atmospheric concentrations despite the fact that the value for the indicator is low. At present, the atmospheric concentration of CO_2 is 25% higher than its pre-industrial level, and the concentration is increasing at approximately 0.5% per year. This increase is mainly due to the flow from the lithosphere which is reflected in indicator $I_{1,1}$. Here emissions due to deforestation are also included in the indicator values.

However, when an environmental problem is known and detailed modelling studies exist relating emissions to atmospheric concentrations, it could be more useful to develop indicators that directly measure how far the present rate of emissions is from the level which does not give rise to any increase in the ecosphere. In the case of CO_2 there are, of course, several such studies. IPCC (1995) estimates that in order to stabilise atmospheric concentrations at 350 ppm (slightly below the present level) by the year 2100, the accumulated emissions from 1990 to the end of the 21st century must not exceed some 300–430 Gton C. This implies an annual average rate of carbon emissions equal to 3.3 ± 0.6 Gton C/year. [4] This value could be referred to as a sustainable level of CO_2 emissions (given that the climatic changes associated with the present atmospheric concentration of CO_2 are acceptable) and a sustainability indicator for CO_2 emissions could be defined as the ratio between the present and the sustainable emission rates. If this ratio is equal to unity, then the present emissions are sustainable. At present, we estimate it to lie in the range 1.5 to 3.0.

4.2.2. Indicators for substances that are foreign to nature

The number of chemicals used in society has virtually exploded. In the present industrial society tens of thousands of chemicals are used regularly. There are, for example, over 70 000 chemicals on the U.S. TSCA (Toxic Substances Control Act) Inventory (Clements et al., 1994). We know that the links between emissions, ecospheric concentrations and damage are often characterised by long time lags and a high degree of complexity.

This means that it is extremely difficult to predict the environmental consequences of an emission of a specific substance to the ecosphere. But how should we determine which restrictions are needed? According to Principle 2, we should not emit substances to nature at a rate that is faster than they are degraded into naturally existing substances that can be incorporated in the cycles of nature. [5] This in turn implies strong restrictions on the use of persistent [6] substances. Sustainability also implies strong restrictions on the use of substances that have long-term impacts—i.e., substances that might degrade rapidly, but have the potential to reduce biodiversity, that are mutagenic or that affect reproductive systems.

In order to develop indicators that reflect to what extent the present use of artificially produced chemicals is sustainable or not, we first must identify the chemicals that are persistent (including metabolites) or that have long-term impacts, and then we need to find statistics on their emission rates.

Ideally, one would like to compare the emission rates with the degradation rates, but this is not possible for the vast majority of chemicals since the decay processes are very complex and the rate of degradation depends on the specific environment. When there is a lack of emission data, estimates can be made using mass-balance calculations of industrial processes (see, e.g., Ayres et al., 1989 and Ayres et al., 1995).

4.2.2.1. Indicator no. 2,3: production volumes of persistent chemicals foreign to nature. Hence, we suggest that the trend in the production volume of persistent substances should be continuously monitored. The U.S. Environmental Protection Agency has produced a list containing 80 persistent bioaccumulators produced in the U.S. in quantities over 5 tons annually. [7] The OECD has produced a Representative List of High Production

[4] For the 22nd century even stronger reductions are needed in order to avoid a renewed increase of CO_2 in the atmosphere.

[5] The International Joint Commission (1994) writes that "persistent toxic substances are too dangerous to the biosphere and humans to permit their release in any quantity."

[6] Here, persistent substances also include substances that are easily degradeable, but whose metabolites are persistent.

[7] A later version of this list (Clements et al., 1994) included only those chemicals that are produced in quantities over 500 tons/year. This criterion reduced the number of chemicals on the list to 33.

Table 4
The production volumes of common persistent bioaccumulators in the OECD

CAS-number	Chemical name	$I_{2,3}$ = Prod. vol. (kton/year)
1163-19-5	Di-pentabromobenzene ether	US 10, EU 1, JP 1
4904-61-4	1,5,9-Cyclododecatriene	US 10, EU 10
5216-25-1	*p*-Chiorobenzontrichloride	US 10, EU 1
67-72-1	Ethane, hexachloro	US 1, EU 1
77-47-4	Hexachlorocyclopentadiene	US 1, EU 1
79-94-7	Tetrabromo-bisphenol	US 10, EU 1, CH 1, JP 1
95-94-3	Benzene-1,2,4,5-tetrachloro	US 1, EU 1

Source: Smith (1994). Here, EU stands for the European Union, CH for Switzerland and JP for Japan.

Volume Chemicals containing the 1363 most commonly used chemicals in the OECD area. [8] Since all major industrialised countries except the Eastern European countries (including the former Soviet Union) are members of the OECD, data from the OECD could be used as a first indication of the trends in the worldwide production of these chemicals. The combination of the OECD list and the EPA list yielded 7 chemicals (Pettersson, 1994). But, even for these common chemicals the OECD had not available any time series over the production volumes. Data were only available for a single year and only to an order of magnitude accuracy (see Table 4).

This means that there is an urgent need for compiling data on the global production volumes of persistent substances, so that the trend in the use of such chemicals can be established. We have asked three major international organisations [9] whether they have the overall picture of this trend. But none of them could answer the question positively. Hence, it could be useful to develop an indicator that measures the societal knowledge of the global production of persistent substances.

4.2.2.2. Indicator no. 2,4: long-term implication of emissions of substances that are foreign to nature. Here we present an indicator for substances that are foreign to nature, but whose degradation processes can be described by a simple mathematical equation. For such substances, mainly gases emitted to the atmosphere, we will compare the production volumes with the rate of decay. Assume, as in Eq. 4.5, that the decay process of a specific gas can be described by:

$$\dot{M}(t) = E_a - kM(t). \tag{4.7}$$

This is, for instance, possible for radioactive gases and CFCs. Using this representation, we can define a sustainability indicator as the ratio between long-term content of the substance for the present rate of emissions in relation to the present content in the atmosphere. We have:

$$I_{2,4} = \frac{E_a}{kM_{\text{present}}}. \tag{4.8}$$

It should be noted that the indicator $I_{2,4}$ is normalised by the present content in the atmosphere, whereas $I_{2,2}$ is normalised by the pre-industrial content in the atmosphere. This means that the interpretation of the indicator value is different for the two types of indicators. For $I_{2,2} = 1$ the anthropogenic emissions are equal to zero. For $I_{2,4} = 1$ the present anthropogenic emissions will stabilise the present atmospheric concentrations. This could be

[8] The OECD list contains substances that occur on two or more national high volume lists with a production volume of over a 1000 tons/year or on one national list, but with a production volume exceeding 10000 tons/year (Freij, 1994).

[9] The OECD, the European Commission and the U.N. Economic Commission for Europe.

Table 5
Indicator $I_{2,4}$ for substances that are foreign to nature

Substance	$I_{2,5}$
CFC 11	4.4
CFC 12	7.5
CFC 113	14
CFC 114	15
CFC 115	39
HCFC-22	5.3
Methylchloroform	1.4
Carbon tetrachloride	14
Halon-1211	4.2
Halon-1301	190
^{85}Kr	2

All compounds except ^{85}Kr are ozone depleters. For these substances we have used global production data from the year 1985 (German Bundestag, 1989). Since 1985, aggregate production of CFCs has been halved (Brown et al., 1994). For the last compound, ^{85}Kr, a radioactive gas that is emitted by nuclear fuel reprocessing plants, we have used emission data from (UNSCEAR, 1993).

sustainable, but only if the present content in the atmosphere is low enough. This is, for example, not the case for CFCs. Thus, much effort is made to phase out the production of CFCs.

If $I_{2,4} > 1$ the present rate of emissions will cause the atmospheric content to increase. The long-term stationary state content of the gas for a specific production rate is given by the value of the indicator multiplied by the present content.

When a time series is based on this indicator, it is possible to fix the normalisation coefficient, $M_{present}$, at a specific year, so that the trend of the emissions is reflected by the indicator.

For the ozone-depleting substances (see Table 5), we have used production data. Emission data for ozone depleters are more uncertain than production data since emissions are due to leakage from the technosphere. This means that our indicator value is only valid if the entire production volume eventually leaks out. The present global destruction rate of ozone depleters is negligible in comparison to production rates, but this will hopefully change in the near future.

4.2.2.3. Some other desirable indicators for Principle 2. So far we have mainly discussed substances that are intentionally produced, but significant problems also arise from the unintentional production of substances that are foreign to nature. Such production occurs in chemical industries, in incinerators, at waste deposits where substances might react, etc. Several such substances have been identified as very persistent, bioaccumulating and extremely toxic (e.g., dioxin). However, there is a significant lack of data on the production volumes of unintentionally produced substances and many of them even remain unidentified.

In order to make any indication early in the causal chain, we suggest that focus is put on processes that are known to give rise to unintentional production of substances that are foreign to nature.

Finally, an indicator for the production of substances that are not themselves persistent, but that have long-term impacts (e.g., that are mutagenic), that affect reproductive systems or cause losses in biodiversity, would be desirable.

4.3. Indicators for Principle 3

The global population is expected to nearly double by the year 2050 (United Nations, 1992b). In order to provide a sustainable supply of biomass for food, material and energy for the growing population, we need to maintain the services of the ecosystems. These services include, for example, generation and maintenance of soils, disposal of wastes and cycling of nutrients, pest control and pollination (Ehrlich and Ehrlich, 1992). This means that the productivity of lands and the biodiversity of ecosystems must not worsen. This is the essence of Principle 3.

Human activities threaten ecosystem productivity and biodiversity in two ways. The exchange of substances between society and nature is dealt with by the indicators for Principles 1 and 2. In this section we focus on societal activities that by manipulation or harvesting of ecosystems may threaten sustainability and, in particular, biodiversity and ecosystem productivity.

4.3.1.1. Manipulation and harvesting. Principle 3 deals with harvesting and manipulation of ecosystems. Harvesting of funds includes activities such as hunting wildlife, catching fish, harvesting trees, groundwater extraction, etc. Holmberg and Karlsson (1992) discuss three ways of manipulation:

(i) we can displace nature (by forcing away or disturbing ecological systems or geophysical systems—e.g., by construction of cities, airports, etc.),

(ii) we can reshape the structures of nature (by damming of rivers, ploughing, reforestation, deforestation, etc.),

(iii) we can guide processes and flows (by gene manipulation, animal and plant breeding, etc.).

Since our ambition is to develop indicators that focus on the societal activities that give rise to changes in the state of the environment, indicators for Principle 3 should focus on those aspects of societal manipulation and harvesting of nature that are not sustainable rather than focusing on the environmental consequences of the unsustainable methods. A large set of indicators can be found in the work by Vitousek et al. (1986), in which the anthropogenic use of biomass is compared to net primary production (NPP) in various ecosystems. For example, it is reported that 40% of terrestrial potential NPP is used directly, co-opted, or foregone due to anthropogenic manipulation or harvesting of the ecosystems. Below, we will present a number of other indicators that are relevant for Principle 3.

4.3.2. Large-scale transformation of lands

Since the beginning of the 18th century, humanity has carried out a large scale transformation of the Earth's ecosystems and productive surfaces (see Fig. 3). The area used for crops and grass lands has increased dramatically at the expense of huge losses of primary forests. In the long run this trend is obviously not

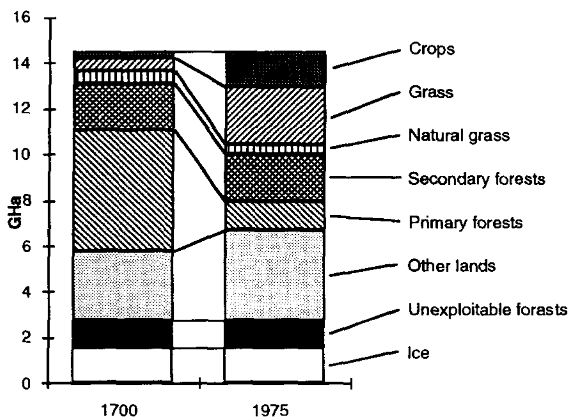

Fig. 3. Global land use. It is clearly shown that crops and grass lands have increased at the expense of primary forests. *Source:* Buringh and Dudal (1987).

sustainable due to limited land area. Furthermore, it violates both the second principle [10] and the third (e.g., systematic losses of biodiversity).

4.3.2.1. Indicator no. 3,1: transformation of lands. This means that it is of primary interest to focus on the amount of land diverted to different purposes. It should be stressed that such an indicator is useful for global, regional, national as well as local planners and decision makers. It could be presented as in Fig. 3.

The present total annual loss of crop land is estimated at more than 10 Mha, of which soil erosion is responsible for 5–7 Mha/year, urban expansion 2–4 Mha/year and salinization and water logging 2–3 Mha/year (Kendall and Pimentel, 1994). There is, however, a considerable crop land gain in the order of 16 Mha/year which is achieved by deforestation.

Below we present a few examples of indicators for the anthropogenic use of the different types of lands—i.e., agricultural and forest areas, as well as oceans and lakes. These indicators should focus early in the causal chain.

4.3.3. Indicating use of land areas

Agriculture affects both the productivity of soils and biological diversity. Losses in soil productivity occur as a result of a number of changes in soil quality: e.g., soil erosion, nutrient runoff, water logging, desertification, compaction, crusting, organic matter loss, salinization, nutrient depletion by leaching, toxicant accumulation and acidification. Losses in biodiversity could also affect the productivity of soils, and changes in soil quality can have a negative impact on biodiversity.

Toxicant accumulation and acidification are related to Principles 1 and 2 and, thus, indicators early in the causal chain for substances causing these problems have already been discussed in Sections 4.1 and 4.2, respectively. Here, we will focus on agricultural practices that cause some of the other problems listed above.

4.3.3.1. Indicator no. 3,2: soil cover. Soil erosion is the single most serious cause of degradation of land (Kendall and Pimentel, 1994). It is caused by both water and wind. It is estimated that water erosion affects 560 Mha of lands whereas wind erosion affects 200 Mha (Craswell, 1993). Erosion exists naturally, but it can be enhanced by anthropogenic mismanagement of lands. Although erosion is a complicated process, there is a general consensus that the most important reason for the widespread existence of erosion is agricultural practices that leave the soil without cover (Kendall and Pimentel, 1994).

An indicator early in the causal chain for soil erosion would then be the ratio between crop land which is sufficiently covered [11] L_c and the total amount of crop land L_T:

$$I_{3,2} = \frac{L_c}{L_T}. \tag{4.9}$$

There are, of course, other measures that can be taken in order to prevent soil erosion, but soil cover is the most important.

Soil erosion also creates a number of other problems further downstream (e.g., flooding, silting of dams and damage to coral reefs). Indicators for such problems will not be given here since these problems are indicated by environmental quality indicators.

Other indicators early in the causal chain that need to be developed for the use of agricultural lands and agricultural practices are indicators that focus on irrigation (malpractised irrigation gives rise to salinization),

[10] Deforestation is presently estimated to give rise to net emissions of CO_2 amounting to approximately 1.9 Gton C/year (Sigenthaler and Sarmiento, 1993).

[11] Sufficiently covered is a vague concept, but it implies that the degree of cover ensures that the rate of erosion does not exceed the rate of soil renewal. This means that the degree of cover will differ from region to region depending on the natural circumstances.

Table 6
Base cation losses from Swedish forest soil due to actual stem harvesting and possible future whole-tree harvesting

	Mg^{2+}	K^{+}	Ca^{2+}
Actual stem harvesting	84%	24%	97%
Possible future whole-tree harvesting	91%	79%	100%

The figures in the table indicate the percentage of the Swedish forest area that is losing base cations.
Source: Based on Olsson et al. (1993).

nutrient balance in agricultural soils, agricultural practices affecting species and genetic diversity (e.g., monoculture, animal and plant breeding and genetic modification of plants and animals).

4.3.3.2. Indicator no. 3.3: nutrient balance in soils. A basic principle for the long-term sustainability of land use is that harvest rates do not systematically exceed growth rates. This principle also applies to the nutrients in the soil. In the long run, the sustainability of the ecosystem cannot be maintained if nutrient export exceeds nutrient input to the soils. With respect to nutrient decline in soils, increased harvesting has similar effects on the ecosystems as acidification resulting from air pollutants. Increased biomass harvesting leads to increased export of mineral nutrients from the soil. It is therefore of importance to indicate the long-term nutrient balance in soils. A long-term base cation balance can be written:

$$I_{3,3} = \Delta BC_s = BC_w + BC_d + BC_r - BC_l - BC_u, \qquad (4.10)$$

where ΔBC_s is the change in the stock of a specific base cation in the soil, BC_w the weathering rate, BC_d the deposition rate, BC_r anthropogenic return rate, BC_l the leaching rate and BC_u the net uptake of base cations in biomass.

The stock of base cation in Swedish forest soils has decreased by about 1% per year in the past 30–50 years (Falkengren-Grerup et al., 1987; Hallbäcken, 1992). Of this decrease, about half is due to biomass uptake and the other half is due to leakage caused by acidification (Berdén et al., 1987).

In Table 6 we have indicated the share of the Swedish forest area where the stock of base cations are decreasing (the share of the Swedish forest area where $\Delta BC_s < 0$). [12] The table also includes information about the share of the Swedish forest area that would have a decreasing stock of base cations if increased biomass utilisation, in the form of whole-tree harvesting, would be practised in the future.

Leaching of base cations exceeds atmospheric input for almost all Swedish field experiments where nutrient fluxes have been investigated (Falkengren-Grerup et al., 1987). However, even if BC_d and BC_l were excluded from Eq. 4.10, ΔBC_s for Ca would be negative for a large share of Swedish forest area, if stem harvesting is practised, and for all three base cations if whole-tree harvesting would be practised. Even if we can reduce the acidification caused by air pollutants, a sustainable long-term forestry will require a supply of nutrients to the forest soils—e.g., by returning ashes (i.e., by increasing the anthropogenic return rate).

4.3.3.3. Indicating biological diversity of forest land. There are mainly two groups of socio-ecological indicators for the biological diversity of forest lands: (i) indicators that focus on preserved zones (e.g., by comparing the area that is preserved with the total area) and (ii) indicators that focus on methods of forestry.

When indicating the methods of forestry, there are different aspects that are important (e.g., the share of old, large and/or dead trees, drainage by ditches, use of pesticides and introduction of foreign species). The Forest

[12] The figures in the table are only valid for forest soils deeper than 70 cm. If thinner soils were included, the share of areas with ΔBC_s < 0 would be somewhat greater.

Stewardship Council (an international NGO) is developing criteria and principles that take these aspects into account.

4.3.4. Indicating use of marine and lake resources

The status of marine resources is affected by pollution as well as harvest rates and harvest methods. Methods for indicating the sources of pollution are developed in Sections 4.1 and 4.2, respectively.

The intensity of the use of marine resources is a serious problem, and indicators for this societal activity is needed. The total world fish catch has increased from 22 million tons in 1950 to a level of 100 million tons (1988–1992). In all the major fishing areas in the world this catch relies on a yield that is at or beyond the limit for sustainability (Brown et al., 1994). A growing world population implies that the catch per capita must decrease. In 1988 the annual per capita catch peaked at 19.4 kg, but according to preliminary data for 1993, it has decreased to 17.6 kg.

4.3.4.1. Indicator no. 3,4: harvesting of funds. A typical indicator for harvesting (e.g., of a fish population) is the yield divided by the growth:

$$I_{3,4} = \frac{h}{g}, \tag{4.11}$$

where h is the harvest per year and g is the annual growth.

The *maximum sustainable yield* (MSY) is the maximal yield that can be achieved by harvesting a population at the same time as a stationary population size is maintained. Since the MSY concept focuses on the long-term sustainable yield from an ecosystem, it can serve as a basis for discussions on management of harvesting (May et al., 1979). The concept has been criticized, though, for not taking into account the stability of the system. Results from studying model systems suggest that when harvesting at the MSY, there is a risk of overexploita-

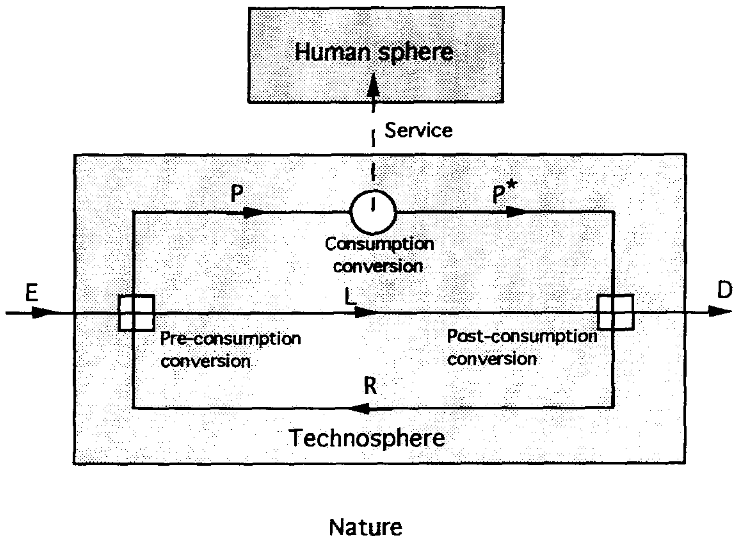

Fig. 4. A schematic illustration of the physical flows within the technosphere. Substances extracted from nature (E) and substances recycled within in the technosphere (R) are converted into products P and losses L caused by the preconsumption conversion. (Some substances—e.g., the elements—may be turned into products without conversion.) P delivers services to the human sphere when used in the consumption conversion. After consumption, used products P together with L are possibly converted, and thereafter sent into the recirculated fraction R or are discharged to the ecosphere (D) (Holmberg and Karlsson, 1992).

tion leading to the extinction of the harvested species (see, e.g., Beddington and Cooke, 1982). This is especially important if the harvest rate is controlled by fixed catch quota. Uncertainties about the fish stocks may lead to harvest yields that destabilize the ecosystem. In a recent study of a three-species model (Azar et al., 1995), we have compared the stability of two harvesting strategies—(i) constant quota and (ii) constant effort—showing that constant catch quota can lead to both oscillations (and chaos) and an increased risk of overexploitation.

4.4. Indicators for Principle 4

Principles 1, 2 and 3 constitute the framework for a sustainable influence on nature. Principle 4 states that if we want a prosperous society within this framework, the societal metabolism must be efficient and just. This principle covers four aspects: overall efficiency, inter- and intragenerational equity, and basic human needs. Below, we develop indicators for some of these aspects.

4.4.1. Indicator no. 4,1: overall efficiency

A simple schematic description of the societal metabolism is given in Fig. 4. The overall efficiency indicators are measures of the productivity in the technosphere. They indicate how much service [13] that is delivered for a certain amount of resources extracted from nature, normalized with respect to the situation a certain year y:

$$I_{4,1} = \frac{\dfrac{\text{Service}}{E}}{\dfrac{\text{Service}_y}{E_y}}. \tag{4.12}$$

It is also possible to complement the overall efficiency indicators with specific efficiency indicators that focus on the internal conversion in the technosphere—e.g., the flow P per unit of total input $E+R$, or the recirculation R compared to the total input $E+R$,

$$\eta_1 = \frac{P}{E+R};\ \eta_2 = \frac{R}{E+R}. \tag{4.13}$$

The recirculation flow R can also be compared to the total output $P^* + L$:

$$\eta_3 = \frac{R}{P^* + L}. \tag{4.14}$$

In a stationary state P equals P^* and E equals D. It is possible to normalize the efficiencies with normalization values η_n determined according to various principles: a normalization to the maximum possible theoretical value, to the best available technology (BAT), or to a desirable value. We get complementary efficiency indicators:

$$I_i = \frac{\eta_i}{\eta_n}, \tag{4.15}$$

where $i = 1, 2, 3$. In Table 7 some examples of overall efficiency indicators are shown. We can see, for instance, that the supply of food per hectare of land has increased, whereas the supply of food per phosphate input has decreased since 1970.

[13] The service flows can be the temperature of a room, the light from a bulb, etc. The physical flows can be, for instance, energy, exergy, different kinds of materials or products. It is important to note that through increased efficiency it is possible to increase the rate of service flow without increasing the exchange with nature (i.e., inputs of energy and materials and emissions of waste).

Table 7
Overall efficiency indicators

Efficiency indicators	1970	1980	(1987) 1990
Food			
Calories in food/Phosphate input (World)	1	0.67	(0.61)
Proteins in food/Phosphate input (World)	1	0.66	(0.60)
Fats in food/Phosphate input (World)	1	0.69	(0.67)
Calories in food/Area input (World)	1	1.03	(1.08)
Proteins in food/Area input (World)	1	1.01	(1.07)
Fats in food/Area input (World)	1	1.07	(1.18)
Energy			
GDP/Primary energy input to the World (USD/J)	1	1.07	1.21
GDP/Primary energy input to Sweden (USD/J)	1	1.06	1.12
Dwelling area/Primary energy input to the dwelling sector in Sweden (m^2/J)	1	1.11	1.14
Personal transport/Primary energy input to personal transport in Sweden (Pers. km/J)	1	0.91	0.99
Goods transport/Primary energy input to goods transport in Sweden (ton km/J)	1	1.06	0.93

The values are normalized to the year 1970.
Sources: Bumb (1989), FAO Food Balance Sheet (FAO, 1991), Schipper et al. (1994) and Brown et al. (1994).

As an example of a complementary specific efficiency indicator we have chosen to indicate the efficiency of the use of nutrients in the Swedish agricultural system. This indicator is defined as;

$$\eta = \frac{\text{Nutrients in provisions from the Swedish agricultural system}}{\text{The supply of nutrients to the Swedish agricultural system}} \tag{4.16}$$

The supply of the nutrients N, P and K in fertilizers (excluding manure), imported cattle feed, deposited nitrogen and biologically fixed nitrogen are 111, 15 and 23 kg/ha, respectively (Granstedt and Westberg, 1992). The content of nutrients in provisions (vegetable and animal food) harvested in Sweden are 29, 6 and 6 kg/ha (Granstedt and Westberg, 1992). The differences between these figures are losses due to leakage, sorption, volatilization, etc. The efficiency indicators for the use of nutrients in the Swedish agricultural system in 1990 are then:

$$\eta_N = \tfrac{29}{111} = 26\%$$

$$\eta_P = \tfrac{6}{15} = 40\%$$

$$\eta_K = \tfrac{6}{23} = 26\%$$

4.4.2. Indicator no. 4,2: intragenerational justice

The intragenerational justice indicators are measures of an uneven distribution of services and resource use. These indicators can be defined as the amount of services delivered per capita in a specific region (e.g., a country) compared to the amount of services delivered per capita in a reference region (e.g., the world):

$$I_{4,2} = \frac{\text{Supply to region A per capita}}{\text{Supply to reference region per capita}}. \tag{4.17}$$

Obviously this indicator will not reflect unequal distributions of income within the specific region.

Table 8 gives some examples of intragenerational justice indicators, where we have compared the use of energy and food per capita in Sweden with the global per capita use. The global per capita use of primary energy approaches the Swedish use, but the Swedish per capita use is still much higher than the global use.

Table 8
Intragenerational justice indicators

Intragenerational justice indicators	1970	1980	(1987) 1990
Food			
Calories per capita in Sweden/Calories per capita in the World	1.18	1.17	(1.13)
Proteins per capita in Sweden/Proteins per capita in the World	1.35	1.43	(1.37)
Fats per capita in Sweden/Fats per capita in the World	2.11	2.14	(1.98)
Energy			
(Primary energy per capita in Sweden)/(Primary energy per capita in the World)	7.3	5.8	3.8

Sources: FAO Food Balance Sheet (FAO, 1991) and Schipper et al. (1994).

4.4.3. Indicator no. 4,3: intergenerational justice

These indicators should cover aspects related to the use of non-renewable resources over time. It is important to note that non-renewable resources must not necessarily be kept in the lithosphere, but may be equally or even more valuable to future generations if they are kept in ''closed'' cycles within the technosphere. One rough indicator along these lines could be:

$$I_{4,3} = \frac{X_L}{X_R + X_T}, \tag{4.18}$$

where X_L is the annual loss of the resource due to dissipative use, and X_R and X_T represent the available amount of the resource in the lithosphere and the technosphere, respectively (see Fig. 1). The inverse of $I_{4,3}$ gives the time it would take before the resource would be exhausted (given constant annual losses and no new discoveries). If X_L represents the accumulated loss, this indicator would show how much we have used in comparison to how much we have left.

4.4.4. Indicator no. 4,4: basic human needs

The human needs indicators aim at indicating to what extent basic human needs are satisfied. Streeten et al. (1981) suggest that one could choose a few basic indicators that together reflect the fulfilment of basic needs (see Table 9). The exact formulation of needs and corresponding indicators should be left to the experts of the different sectors. Many indicators of this kind are already calculated by the United Nations (e.g., literacy, infant mortality rate, life expectancy, calorie supply, etc.).

A possible basic human needs indicator is given by:

$$I_{4,4} = \text{The share of the population that does not get their basic needs fulfilled.} \tag{4.19}$$

Table 9
Basic needs and corresponding typical indicators

Basic needs	Typical indicator
Food	Per capita daily calorie intake as a percentage of requirements
	Percentage of population with adequate food intake
Water and sanitation	Percentage of population with access to potable water
	Percentage of population with access to sanitation facilities
	Infant mortality per thousand births
Health	Life expectancy at birth
Education	Literacy
	Primary school enrollment as a percentage of the population aged 5 to 14

Source: Based on Streeten et al. (1981).

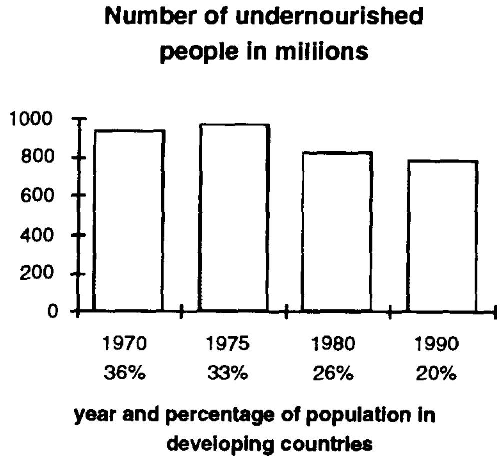

Fig. 5. The number of people in developing countries who are chronically undernourished, using data from Uvin et al. (1994). It should be noted that undernourishment has decreased since 1970, in both absolute and relative terms.

A typical basic needs indicator is the number of chronically undernourished people: i.e., people who on average during the course of a year do not consume enough food to maintain their weight and engage in light activity (according to FAO): see Fig. 5 (Uvin et al., 1994).

5. Discussion and conclusions

The main result of this paper is the *method* for developing socio-ecological indicators for sustainability. Such indicators should be (i) based on a framework for sustainability (the four socio-ecological principles for sustainability) and (ii) focus early in the causal chain.

Practical experience from Swedish companies and local authorities has shown that the socio-ecological principles that we have used as a systematic framework, function well when making strategic decisions. Today 40 Swedish municipalities and 20 larger Swedish companies use these principles in their strategic planning processes (Holmberg et al., 1996; Robèrt, 1994).

It is also our experience that the focus for future work with environmental issues is shifting from discussion and investigations of environmental effects (environmental pathology) to strategical planning of the societal metabolism (societal prophylaxis). This implies that there is a need for indicators that focus early in the causal chain—i.e., that put focus on the activities in society. This does not mean that the socio-ecological indicators can replace the traditional environmental quality indicators. But we think that they will make a necessary complement to indicators that focus later in the causal chain.

The main reason for focusing early in the causal chain is that we want to capture also societal activities that are potentially unsustainable. In cases where the causal chain and the environmental effects are known, and the time lags are small, the reason for focusing early in the causal chain is not that strong. In these cases it is possible to aggregate emissions into an overall index (see, for instance, the so-called theme indicators developed by Adriaanse (1993) for climate change, depletion of the ozone layer, acidification and eutrophication).

There are no exact limits defining sustainability. Instead, the border between sustainability and unsustainability is not sharp. This means that it is not possible to determine exact reference values for sustainability. However, many of the societal activities today are far from sustainable, which means that time series of the indicators would enable us to say whether sustainability is approached or not.

Table 10
Socio-ecological indicators based on socio-ecological principles

Principle 1: Substances extracted from the lithosphere must not systematically accumulate in the ecosphere	*Principle 2:* Society-produced substances must not systematically accumulate in the ecosphere	*Principle 3:* The physical conditions for production and diversity within the ecosphere must not systematically be deteriorated	*Principle 4:* The use of resources must be efficient and just with respect to meeting human needs
$I_{1,1}$: Lithospheric extraction compared to natural flows	$I_{2,1}$: Anthropogenic flows compared to natural flows	$I_{3,1}$: Transformation of lands	$I_{4,1}$: Overall efficiency
$I_{1,2}$: Accumulated lithospheric extraction	$I_{2,2}$: Long-term implication of emissions of naturally existing substances	$I_{3,2}$: Soil cover	$I_{4,2}$: Intragenerational justice
$I_{1,3}$: Non-renewable energy supply	$I_{2,3}$: Production volumes of persistent chemicals	$I_{3,3}$: Nutrient balance in soils	$I_{4,3}$: Intergenerational justice
	$I_{2,4}$: Long-term implication of emissions of substances that are foreign to nature	$I_{3,4}$: Harvesting of funds	$I_{4,4}$: Basic human needs

We have suggested specific indicators for each of the four principles (see Table 10). This broad approach implies that some of the indicators should be considered as preliminary (especially the indicators for Principles 3 and 4). Still, one advantage is that it offers a point of departure for future work on indicators which takes an integrated approach to sustainability. It is our hope that our formulation of indicators will inspire future research in this area.

In future work we shall develop the indicators further. For policy purposes it is important that the number of indicators is relatively small. Therefore, we will investigate the possibility of aggregating some indicators: e.g., the indicators for lithospheric extraction for each element into an index for all elements or groups of elements. It is also of importance to display time series of the indicators.

We shall also apply socio-ecological indicators to regional and local situations, and make the method accessible to planners and decision makers at regional and local administrative levels of society. In an ongoing project we are studying the resource use of the island of Gotland in Sweden. Here, special emphasis is given to problems related to the responsibility of material flows between regions (Carlson et al., 1995).

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