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The ecological footprint from a systems perspective of sustainability

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SUMMARY

The Ecological Footprint (EF) is a method for estimating the biologically productive area necessary to support current consumption patterns, given prevailing technical and economic processes. By allowing to compare human impact to the planet's limited bioproductive area, this method tests a basic ecological condition for sustainability. The ecological footprint has gained popularity for its pedagogical strength as it expresses the results of its analysis in spatial units that can easily be communicated. Many EF estimates have been performed on a global, national and sub-national level. In this paper, we review the method and critically assess it from a sustainability perspective based on first order principles. We examine:

- which aspects of sustainability are already covered by existing EF assessments;
- which further aspects of sustainability could be made accountable through the EF (such as areas needed to assimilate waste streams that are not yet accounted for in present assessments); and
- those aspects of sustainability that cannot be accountable through the EF, thereby needing complimentary auditing tools.

Since the EF is a measure of renewable biocapacity, we argue that some dimensions of ecological sustainability should not be included in the EF. These include human activities that should be phased out to obtain sustainability, such as emissions of persistent compounds foreign to nature and qualitative aspects that represent secondary uses of ecological areas and do therefore not occupy a clearly identifiable additional ecological space. We also conclude that the EF is useful for documenting the overall human use or abuse of the potentially renewable functions and services of nature. Particularly, by aggregating in a consistent way a variety of human impacts, it can effectively identify the scale of the human economy in comparison to the size of the biosphere.

INTRODUCTION

'You get what you measure' underlines the technical and psychological rationale of tracking progress in order to make progress happen. Therefore, to make sustainability happen, we need tools to monitor progress - and, they need to be consistent with the basic conditions of sustainability. A critical evaluation of performance measures from the perspective of a coherent and comprehensive sustainability framework is not only helpful in the elaboration of more encompassing monitoring programs, but will also strengthen the application of such frameworks. This paper examines a performance measure, the ecological footprint, from a systemic sustainability perspective defined by four first order principles.

The Ecological Footprint (EF) concept, introduced by Rees and Wackernagel (e.g., 1994), measures the biologically productive area necessary to support current consumption patterns, given prevailing technical and economic processes. The latest estimates show that, on average, a Canadian requires close to 7 hectares of ecologically productive land and 1 hectare of ecologically productive marine area to provide for his or her current level of consumption (Wackernagel *et al*, 1997). These 8 hectares (in total) are the equivalent to more than ten soccer fields. In comparison, the average American occupies a footprint approximately 30 percent larger; the average Italian, one third smaller. The average Swede occupies over 6 hectares. There is solid evidence that these figures may be underestimates of the biologically productive areas necessary to produce the resources these people consume and to assimilate the corresponding waste they generate, all using the existing technology.

Dividing all the biologically productive land and sea on this planet by the number of people inhabiting it results in an average of 2.3 hectares per person, less than one third of what is necessary to accommodate a typical Canadian footprint. If we put aside 12 percent of the biologically productive space for preserving the other 30 million species with whom we share this planet (WCED, 1987) which, by the way, is politically ambitious but ecologically insufficient, the available space per capita shrinks to 2 hectares. With an anticipated global population of 10 billion for the year 2050, the available space will be reduced to 1.2 hectares per person. Already, the average Italian uses 210 percent more than is available on a per capita basis worldwide, or 320 percent more than is at hand per Italian within their national territory. Sweden is still one of the fortunate few countries whose ecological footprints are smaller than their national biologically productive space. Worldwide, however, humanity's footprint may exceed global carrying capacity by 30 percent - in other words, humanity consumes more than what nature can regenerate and is decreasing the globe's natural capital stock. It is not only the non-renewable and renewable resources that are declining but also the ability of nature to assimilate the waste (for example, emissions of carbon dioxide or acidifying substances).

The ecological footprint builds on a variety of earlier analytical attempts to measure human load in order to estimate the dependence of human life on nature (see for example Martinez-Alier (1987) and Cohen (1995)). Much intellectual ground-work for more recent studies was laid in the 1960s and 1970s, particularly by initiatives such as Georg Borgstrom's analysis of 'ghost acreage' (1973), Howard Odum's energy analysis examining systems through energy flows (1994), Jay Forrester's advancements on modeling world resource dynamics as presented by the Club of Rome (Meadows *et al*, 1972; Meadows *et al*, 1992), John Holdren and Paul Ehrlich's IPAT formula (1974), or, in the spirit of the International Biological Programme, Robert Whittaker's calculation of net primary production of the world's ecosystems (Whittaker, 1975; Lieth and Whittaker, 1975).

The last ten to fifteen years have witnessed exciting new developments of tools that measure people's use of nature: life cycle assessments (Abel *et al*, 1990), energy analyses and energy-based lifestyle appraisals (Pimentel *et al*, 1994; Hofstetter, 1991), environmental space calculations going back on ideas of Johann Opshoor and further developed by the Friends of the Earth (Buitenkamp *et al*, 1993), human appropriation of net primary production (Vitousek *et al*, 1986; Fischer-Kowslaski, 1997), documentation of regional and industrial metabolisms (Ayres and Simmonis, 1995), mass intensity measures such as Mass Intensity per Unit of Service (MIPS) (Schmidt-Bleek, 1994), measures of human processes such as the Sustainable Process Index (SPI) (Krotscheck and Narodoslawsky, 1996), socio-ecological indicators (Azar *et al*, 1996), resource accounting input-output models (Duchin and Lange, 1994), computer based spatial models analyzing land-use developments and ecological potentials (Hall *et al*, 1995), computer-based scenario models such as 'PoleStar' (Gallopin *et al*, 1997), or the above mentioned ecological footprint assessment (Wackernagel and Rees, 1996; Folke *et al*, 1997), to name a few.

Most of these tools are accounting systems which document mass balances of renewable and non-renewable resources. Their results are expressed in terms of energy, mass or space, or a combination of these units. While their applications and representations vary, their aim is the same: to quantify human use of nature in order to motivate and implement a reduction of human impact.

The ecological footprint has gained popularity for its didactic strength as it expresses the results of its analysis in spatial units that can easily be communicated and which allow for the comparison of human consumption directly to nature's limited productivity. Also, it is one of the few measures that aggregate a variety of human impact in consistence with thermodynamic laws and ecological principles. Therefore, it becomes an attractive tool for communicating about, teaching and planning for sustainability.

Tools for monitoring the progress towards sustainability are only useful if they build on an explicit definition of sustainable development. This has, for instance, been pointed out by Mitchell (1996) who also argues that a serious shortcoming of many indicator programs is their lack of such principles. A critical evaluation of various indicator programs from a sustainability perspective based on such principles would not only be helpful in elaborating more comprehensive indicator programs, but would also make it easier to determine how they relate to each other. In this paper, we study the ecological footprint method from a sustainability perspective defined by four first order principles (Holmberg *et al*, 1996). We discuss:

- Which aspects of sustainability are presently covered by the EF method;
- Which further aspects of sustainability could be made accountable through EF; and,

- What areas of sustainability cannot be accountable through EF, thereby needing complimentary auditing tools.

To provide a basis for the discussion, we first give a structure for sustainability. This structure is then used as the framework for the assessment of the EF. We also discuss what qualities of the EF are particularly effective for measuring and communicating progress as defined by the first order principles for sustainability, thereby assisting people in the private and public domain in applying these principles.

A STRUCTURE FOR SUSTAINABILITY

Humans are dependent on the ecosphere (the part of the Earth where life exists and the upper stratosphere), and cannot withstand a systematic shift of the physical situation within the ecosphere, e.g., systematic increase in concentration of CO_2, metals and chemicals or systematic decrease of productive soils, pH, fresh water etc. Humans can destroy the functions in the ecosphere by:

1. a systematic net increase in concentration of matter that is introduced into the ecosphere from outside the system;
2. a systematic net increase in concentration of matter that is produced within the ecosphere;
3. a systematic physical deterioration (through harvesting and manipulation) of the ecosphere's ability to utilize waste as building blocks for production, and to provide other essential functions.

Starting from these fundamental and different ways for a society to destroy the functions of the ecosphere, four principles for sustainability have been developed (Robèrt, 1992; Holmberg *et al*, 1996; Holmberg and Robèrt, 1997; Robèrt *et al*, 1997): In order for a society to be sustainable, nature's functions and diversity are not systematically:

I. ... subject to increasing concentrations of substances extracted from the lithosphere;

II. ... subject to increasing concentrations of substances produced by society;

III. … impoverished by over-harvesting or other forms of ecosystem manipulation, i.e., decreasing the thickness of the productive soils, nutrient contents, ground water, genetic variation etc.

Together, the three first principles give a framework for ecological sustainability. It implies a set of restrictions within which the sustainable societal activities must be incorporated. Based on that reasoning, a first order principle for the society's internal turnover of resources is formulated – the fourth principle:

IV. ...resources are used fairly and efficiently in order to meet basic human needs world wide.

Clarification of the principles

I. The societal influence on the ecosphere due to accumulation of lithospheric material is covered by the first principle. The balance of flows between the ecosphere and the lithosphere must be such that *concentrations* of substances from the lithosphere do not systematically increase in the whole ecosphere, or in parts of it. Besides the upstream influence on this balance through the amounts of mining and choices of mined minerals, the balance can be influenced by the quality of final deposits, and the societal competence to technically safeguard the flows through recycling and other measures. What concentration can be accepted in the long run depends on properties such as ecotoxicity, here taken in a broad sense to include effects on the geophysical systems, and bioaccumulation. Due to the complexity and delay mechanisms in the ecosphere, it is often very difficult to foresee what concentration will lead to unacceptable consequences. A general rule is not to allow deviations from the natural state that are large in comparison to natural fluctuations. In particular, deviations should not be allowed to increase systematically. Therefore, what must at least be achieved is a stop to systematic increases in concentration. Depending on the characteristics of the substance and the recipient, the critical concentrations differ. In some recipients an increasing concentration of some substances can have a positive effect before a further increase in concentration will be problematic. In other cases the acceptable concentration has already been exceeded.

II. The societal influence on the ecosphere due to accumulation of substances produced in society is covered by the second principle. It implies that the flows of societal produced molecules and nuclides to the ecosphere must not be so large that they can neither be integrated into the natural cycles within the ecosphere nor be deposited into the lithosphere. The balance of flows must be such that concentrations of substances produced in the society do not systematically increase in the whole ecosphere or in parts of it. Besides the upstream influence on this balance through production volumes and characteristics of what is produced, such as degradability of the produced substances, the balance can be influenced by the quality of final deposits, and the societal competence to technically safeguard the flows through measures such as recycling and incineration.

III. The societal influence on the ecosphere due to manipulation and harvesting of funds and flows within the ecosphere is covered by the third principle. It implies that the resource basis for (i) productivity in the ecosphere such as fertile areas, thickness and quality of soils, availability of fresh water, and (ii) biodiversity is not systematically deteriorated by over-harvesting, mismanagement or displacement.

IV. The internal societal metabolism and the production of services to the human sphere is covered by the fourth principle. It implies that if the societal ambition is to meet human needs everywhere today and in the future, while conforming to the restrictions with regard to available resources given by the first three principles, then the use of resources must be efficient in meeting human needs. If we are more efficient, technically, in organisation and socially, more services with the possibility of meeting more human needs can be provided for a given level of impact in nature. Efficiency in that context, if the perspective is large enough, implies not only reduced resource flows per utility, but also improved means of dealing with social issues like equity, fairness and population growth.

Strategic planning towards sustainability

We have previously described a model for strategic planning towards sustainability which is based on these basic principles (Holmberg and Robèrt, 1997). The model, which has also become a key concept of The Natural Step pedagogy, is independent of scale and type of activity, and is already applied by a growing number of business corporations and municipalities in Sweden and elsewhere. It utilizes 'back-casting' (Dreborg, 1997) from attractive visions within a frame set by the principles. This means that the planning procedure is started from a future-oriented perspective. This perspective builds on the assumption that the organization has succeeded in not contributing to the society's violation of the principles. Afterward, a program for transition is planned in retrospect from the future visions based on the question: 'what shall we do today to optimize our chances to get there?'. In other words, the 'future history' of the organization is written. Examples of references on how back-casting can be performed from a future frame, determined by the principles, are Holmberg and Robèrt (1997) and Robèrt *et al* (1997). Since what we do today influences our chances to be successful tomorrow, the back-casting perspective is essential for sustainable development. This perspective is therefore part of our analysis in the next section.

ECOLOGICAL FOOTPRINT FROM THIS SUSTAINABILITY PERSPECTIVE

In this section, we discuss how the EF relates to the four principles for sustainability described in the previous section. We also explain how the EF could be developed to incorporate more aspects of the principles for sustainability. Further, we discuss which aspects of the principles are more relevant to measure using other methods. Before we relate the EF to the four principles, we present, as background, some general properties of the EF concept.

The main question that the Footprint answers is how much biologically productive land would be required on a continuous basis to provide the necessary energy and material resources consumed by a population and to absorb the wastes discharged by that population. An EF analysis, therefore, is close to an assessment of human appropriation of net primary production (or NPP). The principal difference from other NPP studies is that the footprint expresses the results in spatial measurement units rather than energy or mass equivalents.

EF estimates are calculated to account for as many ecological impacts as possible without exaggerating humanity's current impact. For example, optimistic yield figures are used and some impacts are not yet included in the calculations. Also, the estimates do not double count areas that can give several services simultaneously, since this would exaggerate people's true use of nature. Underestimating human use of nature's productivity Ensures that the EF results do not depict the ecological situation as more severe than it is. This chosen strategy secures the widest possible acceptance of the results.

Both people's EF and the biosphere's areas of biologically productive land are expressed in common units: world average land with world average productivity. In most assessments, official data are used – not because they are the most accurate ones, but to delegate responsibility and show that even with the official data, once interpreted from an ecological perspective, significant new conclusions can be generated.

The EF calculations have so far included land for energy supply, food, forest products, and the built environment, degraded areas, and sea space for fishing. For the waste side, the land needed for sequestering CO_2 is included in the EF. There are attempts to include more aspects of the waste side such as phosphorous retention and denitrification (Folke *et al*, 1997; Wackernagel *et al*, 1998).

Principles 1 and 2

Principles 1 and 2 deal with the deterioration of the ecosphere from accumulation and increased concentrations of substances that are either extracted from the earth's crust (principle 1), or produced within the society (principle 2). Accumulation occurs when such emissions exceed the assimilation capacity of the ecosphere.

In order to answer the questions: 'Which further aspects of sustainability could be made accountable through the EF?' and 'What areas of sustainability cannot be accounted through the EF (thereby needing complimentary auditing tools)?', the following aspects have to be checked:

1. if the assimilation capacity of the flow is known;
2. if the assimilation capacity can be estimated indirectly, e.g., by comparing societal flows with natural flows;
3. if the assimilation capacity can be transformed into an area in an adequate way; and
4. if double counting of area can be avoided.

In the following text, we first discuss emissions of carbon dioxide from fossil fuels, and then other substances related to principles 1 and 2 divided into naturally occurring substances (other than carbon dioxide), and compounds foreign to nature.

Fossil fuels and carbon dioxide

There are three different approaches to calculate the footprint of fossil fuel consumption — and all three result in approximately the same area. All three are motivated by the idea that in order to be sustainable, humanity must not undermine functions and biodiversity of the ecosphere. This is the essence of the first three principles for sustainability.

One way to calculate the EF for fossil fuels would be to account for the corresponding area needed for the sustainable production of bio-fuels. The rationale for this way of calculating would be the close relationship between fossil fuels and bio-fuels, such as methane or ethanol. They have the same origin (photosynthesis), they are of similar quality and they can be applied in almost the same technological systems (in combustion engines for instance). The needed productive area for that type of energy supply, built on closed carbon cycles (i.e., no net increase of CO_2 in the atmosphere), would then be the rational basis for the EF calculation. This method would lead to the biggest footprint estimates for fossil fuel. However, there is some considerable controversy about the degree to which biofuels can substitute for the global use of fossil fuels considering the competition for land areas for other purposes like food, materials and biodiversity (Berndes, 1997; Giampietro *et al*, 1997; Hall, 1997).

Another way of calculating the fossil fuel footprint would be to calculate the area needed to compensate only the biochemical energy of the burned fossil, without taking into account that the biochemical energy in the woods has not the same technical quality as fossil fuel or bio-fuels. This would lead to slightly lower ecological footprints for fossil energy.

The third method is based on CO_2 sequestration, arguing that the amount of fossil fuel may not be the limiting factor but rather the absorption of the waste gases. In this method, the area is calculated by assessing the extension of newly planted forest required for sequestering the CO_2 released by the combustion of fossil fuel. Such land serves as a CO_2 sink during a period of between 40 to 100 years, depending on climate and species of forest. In order not to release the sequestered carbon dioxide, the mature forest would have to be left for the future with no harvest, spontaneously renewing itself. As the absorbing forests mature, additional forest areas for CO_2 sequestration would be needed in order to avoid increasing levels of CO_2 in the atmosphere in the case of continued use of fossil fuels. Obviously, this third method leads to the smallest footprints for fossil fuel. It is chosen because it avoids results which could exaggerate human impact of fossil fuel use. Nevertheless, the accumulation of CO_2 in the atmosphere from the use of fossil fuels is only one of many impacts this energy system has in the ecosphere. Therefore, the current conversion rate of 71 gigajoules per hectare and year for liquid fossil fuel — based on sequestration estimates published by the Intergovernmental Panel on Climate Change — are still significant underestimates of this energy's true ecological load on the biosphere (Wackernagel *et al*, 1997). In addition, no significant land area is set aside exclusively to sequester CO_2 from fossil fuel burning (or for the replacement of fossil fuels by wood biomass).

In conclusion, all three methods described above have their limitations. For example, a real transition from fossil fuels to biofuels should lead to a smaller footprint area - current footprint accounting practice, however, would show the opposite. These methods are, though, helpful for the monitoring of increased overall efficiencies of the energy system, as well as the transition towards much more area efficient sources of energy like photovoltaics. (Besides being area efficient, photovoltaics have the additional benefit of not needing to occupy biologically productive surfaces.) The third method has the advantage of giving the smallest area of the three methods and does therefore not exaggerate the area needed. This method is also more relevant when considering emissions of CO_2 from other sources than fossil fuels (for example, cement production since it is not based on a substitute for the energy supply).

Waste assimilation (apart from carbon dioxide)

The waste assimilation, apart from carbon dioxide, has hitherto not generally been considered in EF assessments. Only some newer assessments of the EF include the use of space for breaking down biodegradable waste, particularly in water (Wackernagel *et al*, 1998). In this detailed calculation of the Swedish national footprint, for example, the area of ponds and protective wetland areas which should be needed for effective reduction of the load from leaching plant nutrients from productive agricultural land has been included.

A systematic inclusion of such wastes in EF calculations is difficult since the assimilation capacities in the ecosphere are known only for a few of the naturally occurring substances. In these cases, the anthropogenic flows of such a substance can be converted to an area needed for assimilating that substance. (An example for acidifying substances is given in Box 2.) Relevant anthropogenic flows to consider are actual emissions of substances to the ecosphere or, alternatively, the potential emissions estimated from the extraction rate of virgin substances from the lithosphere or in the case of human made products, the amounts of these substances manufactured. For a region, the net-import of substances should be added to the extraction and production of substances within the region.

When assimilation capacities are not known, it can be possible to indirectly estimate them, for example, by considering some natural flows. The assimilation capacities of metals are usually not known, but can be assumed to be proportional to their natural flows such as in their weathering and sedimentation rates. If the anthropogenic flows of a metal are much larger than the natural flows, the risk increases that such flows will cause accumulation in the ecosphere. The anthropogenic flows of a metal could be converted to an area proportional to an area from which the same amount of metal will be weathering. A difficulty is that the natural concentrations and weathering rates vary for different regions. An example for copper is illustrated in Box 1.

Box 1

As an illustration of how a footprint area can be calculated for a substance with unknown assimilation capacity, we use the anthropogenic flows of copper in Sweden. The emissions of copper (excluding leakage from deposits) have been estimated to 3,000 tonnes/yr (Nilarp, 1994). Since we do not know the assimilation capacity of copper, we compare this value with a natural leakage of copper. An estimate of the natural leakage of copper of 430 g km^{-2} yr^{-1} has been made for agricultural soils in Sweden (Andersson, 1992). This gives a footprint of 7,000,000 km^{-2}.

The net-intake (extraction plus net-import) of virgin copper has been estimated to 88,000 tonnes in Sweden (Nilarp, 1994). This value gives a footprint area of 200,000,000 km^{-2}. This area exceeds the global land area of 140,000,000 km^{-2}. This indicates that there is a *potential* problem with the use of copper in the society and it is most relevant to have a working waste handling system for copper to avoid that large quantities are emitted to the ecosphere in the future.

To avoid double counting of productive areas and erroneously large footprints, one has to consider that the area needed for assimilation of substances can still be made applicable for other purposes, for instance, productive forests and crop-land, provided that these areas are not destroyed because of high concentrations of the emitted compounds. Further, the same area can be applied for the assimilation of more than one compound. We define additive aspects as those that can be added to each other when calculating the total footprint without risk of double counting of area, e.g., food and fiber production. In contrast to exclusive (primary or additive) aspects, the secondary (or non-additive) aspects should not be added to each other since the same area can be used for several of these aspects, e.g., assimilation of substances can be done on the same area as is used for fiber production. Note that built-up land is also an additive aspect but this area cannot be used for assimilation of substances. If none of the emissions of compounds exceed their assimilation capacities corresponding to the productive area needed for additive aspects, there is no need to add any productive area occupied by this function to the footprint area, i.e., $A_{footprint} = A_{additive\ aspects}$. On the other hand, if some of the emissions of compounds exceed their assimilation capacities of the productive area needed for additive aspects, the footprint should increase the more the assimilation is exceeded. The most appropriate strategy would then be to calculate how much the productive area for assimilation of the most dominant compound would need to be extended in order not to have accumulation of that compound, i.e., $A_{footprint} = A_{assimilation} + A_{built\ up\ land}$ (see Figure 1).

The assumption that then needs to be made is that the various compounds would not *influence* each others assimilation thresholds in the ecosystems, or each others impact on the ecosystem. That assumption is often true, but not always. It is definitely not true for various compounds that lead to acidification (like emissions of SO_2 and NO_x), and that add to each others negative effects on area-productivity. On the other hand, this could be adjusted for by simply adding the corresponding areas for such compounds that have additive impacts on the ecosystems productivity into a sum. Here, H^+ equivalents from different compounds could be used. If that sum exceeds the needed extension of the assimilation area for any of the other compounds that can be estimated to be independent of each other, this sum would then be applied to the footprint. And conversely, if any of the 'independent' compounds – say a plant nutrient – has a needed extension of area that exceeds all other areas calculated, including the sum of H^+ assimilating areas, that would be the appropriate area for the footprint, see Box 2.

Box 2

To illustrate how a footprint area can be calculated for substances that add to the same environmental effect and how this area can be added to the *total* footprint area of several environmental impacts, we give an example for emissions of acidifying substances in Sweden. The emissions of SO_x in Sweden are approximately 100,000 tonnes SO_2 yr^{-1} (i.e. 3.1 G eqv H^+ yr^{-1}) and NO_x 380,000 tonnes NO_2 yr^{-1} (i.e. 8.3 G eqv H^+ yr^{-1}) (Statistics Sweden, 1994). The critical load (assimilation capacity) of acidifying substances varies depending on the type of ecosystem. About 70 percent of the total area in Europe has a critical load of less than $20{\cdot}10^{-3}$ eqv H^+ m^{-2} yr^{-1}. The rest of the area has a critical load ranging from 20 to $50{\cdot}10^{-3}$ eqv H^+ m^{-2} yr^{-1} (Wirsenius, 1995). The area needed to assimilate the emissions, assuming a critical load of $20{\cdot}10^{-3}$ eqv H^+ m^{-2} yr^{-1}, would then be 570,000 km^{-2} which can be compared to a previous calculated footprint of Sweden of 440,000 km^{-2} (not counting the built-up area of 80,000 km^{-2} expressed in world average land) in which acidifying substances were not included (Wackernagel *et al*, 1997). This means that the new footprint area, adjusted for acidifying emissions, would be 650,000 km^{-2} (570,000 + 80,000) instead of 520,000 km^{-2}.

Substances for which it is not possible to estimate their assimilation capacities cannot be considered in the EF method and have to be accounted for in some other way. Also, substances that have such low assimilation rates that the EF would become absurdly large may not be compatible with a sustainable society. Since the EF only includes potentially renewable aspects of the human economy, these non-sustainable substances cannot be included in the accounting. Another assessment problem for potentially renewable substances, however, can be to find data for anthropogenic flows of substances such as emissions and the net-intake of substances.

A shift to a substance with lower equivalent impacts (for example a more naturally abundant metal) would give a smaller area for the same amount of anthropogenic flows. This way of calculating substances could thus be used as an indicator measuring the progress towards sustainability.

Compounds foreign to nature

Often compounds that are not normally occurring in the ecosystems cannot be made part of footprinting calculations since assimilation capacities for such substances usually cannot be identified.

Principle 3

Principle 3 deals with harvesting and manipulation of the ecosphere, i.e., displacement, reshaping of structures, and guiding of processes and flows. In a sustainable society, harvesting and manipulation of the ecosphere must not deteriorate the long-term productivity or threaten the biodiversity.

Anthropogenic harvesting and manipulation of the ecosphere can be divided into different activities such as agriculture and forestry. To find out whether different activities are relevant and possible to include in the EF method, we have to check:

1. if the influence on long-term production capacity and biodiversity is known;
2. if the influence on long-term production capacity and biodiversity can be estimated indirectly, e.g., by considering different practices used in the activity such as different types of forestry that affect biodiversity to different extents;
3. if the influence can be transformed into an area in an adequate way;
4. if double counting of area can be avoided.

Built-up land

Paved-over land, built upon land and hydropower dams are counted according to the space they occupy in the present EF method (Wackernagel and Rees, 1996; Wackernagel *et al*, 1997). Areas lost (or damaged) because of industrial activities, including mining, should also be included, but are still left out because of unavailable data.

Forestry and agriculture

Present timber and crop yields are used in most EF analyses, optimistically assuming that these could be maintained. Hence, anthropogenic influence on long-term productivity and biodiversity is underestimated when analyzing forestry and agricultural productivity. Still, badly eroded or otherwise degraded land where the total productivity has been lost is deducted from the bioproductive areas. Biodiversity is considered to the extent that the bio-productive land is decreased by a (probably too small) area set aside to preserve biodiversity (Wackernagel *et al*, 1997; 1998).

The production capacity of forests and agricultural land varies depending on natural factors such as climate and soil. Anthropogenic influence can also affect the production capacity. These effects are covered in EF accounts by including factors that compare local bio-productivity to the global average. When production capacity has been systematically deteriorated on a long-term basis by current practice, this loss should also be reflected in the EF assessments. This, however, has not yet been included, which once more underlines that EF results are underestimates. Loss of conditions for maintenance of biodiversity should also be reflected in the bio-capacity accounts. When lost production capacity and lost biodiversity are known for a specific forestry or agriculture, an area needed to compensate for these losses could be added to the actual forest area or agricultural land in the footprint value. When the losses are not known, template values for losses based on practices used in the forestry or agriculture could be used. For example, a smaller area is needed to compensate for losses when a site-adapted forestry is practiced than when a large-scale conventional forestry is practiced. And, an even smaller area is needed to compensate for losses when an environmentally certified forestry is practiced. In agriculture, for example, the decrease of long-term productivity caused by soil compacting could be estimated based on soil type and machine pressure.

The production capacity can increase when a large amount of fertilizer is used in agriculture. This means that less agricultural land is needed for the same yield. It should be noted that additional areas are needed (such as ponds and protective zones to avoid nutrient leakage) and land to supply the energy (or to assimilate CO_2 emissions) is required for the production of fertilizers. Such aspects could be considered in connection to principles 1 and 2.

For more accurate results, forestry and agriculture should be supplemented by other indicators documenting losses of production capacity and conditions for maintenance of biodiversity, both of which have not yet been captured by EF accounts.

Fisheries

In earlier footprint analyses, we did not include sea space, since the sea does not provide a significant proportion of the food or any other resource humanity consumes (Wackernagel and Rees, 1996). To be more complete, however, present EF analyses now include sea areas to the extent they provide for food (Wackernagel *et al*, 1997). The footprint of the sea is calculated by comparing the fish harvest with the ecological production within an average sea area. Obviously, this is not a sophisticated reflection of the role of the sea but helps to document the magnitude of the various uses of nature.

Studies with a specific focus on the EF of fisheries have been completed by Kautsky *et al* (1997) and Folke *et al* (1998). For more detailed future studies, one could consider not only the amount of fish but also what species are caught since different species have different sustainable yields and also to what extent sea space is lost because of excessive waste loads. This would more clearly point out the potential for overharvest and extinction of fish species, and would make the EF more relevant for indicating the sustainability of humanity's use of the sea. However, since there is significant controversy about the sustainability of fisheries and the impact of waste, and as far more sophisticated assessment methods exist for analyzing marine resources, it may not be particularly effective to use the footprint as an additional assessment tool. Rather, the footprint methodology is effective as a means to present the research results of these more sophisticated assessments in an ecological context.

Water use

Freshwater available in nature can be divided into two forms (which are both recharged from precipitation) (Falkenmark, 1996):

1. as 'green' water in the soil, returning to the atmosphere, and
2. as 'blue' water in aquifers and rivers flowing towards the sea.

The green water directly supports the process of biomass production. Since the transformation of harvested biomass to an ecological footprint has already been covered in the agriculture and forestry section, this water does not need to be accounted again for the footprint analysis. The blue water, on the other hand, can supply households with domestic water, the industry with water for cooling and other processes, and agriculture with irrigation water. The ecological footprint of such a use can be calculated in relation to the amount of the water used.

There are two main categories of the use of blue water:

1. Evaporative (consumptive) water use sending the used water back to the atmosphere after use (i.e., the use of water for irrigation). The ecological footprint of evaporative water use can be calculated as the catchment area that corresponds to the amount of water used. An example of non-sustainable evaporative water use is the decline, caused by irrigation, of ground water in large agricultural areas in the US. The ecological footprint of declining ground water can be calculated as the recharge area of the aquifer that corresponds to the excess use of the actual recharge (renewable yield) of the aquifer.
2. Throughflow-based use (just circulating the water through the societal system), returning it back to the landscape or river after use with a load of pollutants added during use. The ecological footprint of such a use can be based on the pumping energy used and the pollution added and not on the use itself since no water is evaporated.

Besides the actual use of water, the actual supply is decreased through various means of manipulation. Examples are surface hardening through, for instance, growing constructed areas within the technosphere, 'natural' loss of productivity, deforestation, or hardening after drainage.

We are only beginning to incorporate the use of (blue) fresh water in EF analyses, particularly for arid areas (Callejas, 1998). It is included by adding the exclusive bio-productive areas necessary to capture the water, the area necessary to compensate for lost bioproductivity caused by deviated water and areas to cleanse the water again. These areas are not only calculated for the water directly used by a population, but also for producing the goods and services this population receives from elsewhere.

Qualitative impacts on fresh water that will not directly require an additional bio-productive area necessary to remediate it, as in the case of contamination with persistent human-made compounds, requires other measures to track them.

Principle 4

The fourth principle deals with how well the efficiency in the internal societal metabolism and the intra- and intergenerational justice in the distribution of the utilities make it possible to fulfill basic human needs. Population growth is closely connected to these aspects. The equation in Figure 2, which expresses the impact on nature as a product of four factors that humans could change, can be used as a structure when discussing which aspects should be considered for principle 4.

The equation illustrates the dilemma facing humankind – the double challenge inherent in the concept of sustainable development: On the one hand to develop and reach an acceptable service level from material and energy flows for a growing population (principle 4), and in parallel to be able to decrease society's harmful physical influence on nature (principle 1, 2 and 3).

There are four aspects relating to the four factors in the equation that at least have to be considered when discussing the fourth principle. The first factor, **i**, relates to the *transmaterialization* of the societal metabolism. For example, it is diminished by the substitution of less harmful material flows for more harmful ones. The second factor, **m**, relates to the *dematerialization* of the societal metabolism, i.e., more service out of a certain exchange of materials with nature. This can be achieved through reducing the flow (e.g., miniaturization), slowing down the flow (longer life time of products) or through closing the flow (e.g., recycling).

The third factor, **u**, relates to the level of consumption in society. Within a given society, among societies, and also among generations, this factor can vary significantly. The challenge is to find ways in which this factor can be reduced without compromising, or even by increasing, people’s quality of life. The fourth factor, P, relates to aspects that are important for reducing the size, or at least growth rate, of *populations*. This can be achieved through increased access to health care, social security, education and decision-making — particularly for female children and adults. Note that currently 20 percent of the world population (the richest quintile) — or the 'world middle classes' as we may call them — occupies approximately 70 percent of the global footprint. At the same time, the footprint of the rapidly growing poorest sector of humanity may actually be shrinking. For these people, population growth is a primary threat to their health and well-being, while barely affecting the material life of the 'world middle classes'.

Area efficiency

Besides these flow-related aspects, the area efficiency, for example, in agriculture, forestry and energy systems, will become more and more important. Even though most EF results are expressed in global average forest and agricultural productivities, variations of area efficiency between regions and regional changes of area efficiency over time can be documented if specific yield factors replace average figures in footprint calculations.

Transmaterialization and dematerialization

For the flows that are included in the EF calculation, transmaterialization and dematerialization are indirectly considered. If a material that needs less area for assimilation substitutes for a material that needs more, the area for that application will be smaller. And, obviously, if less of a material is needed through dematerialization, the area needed to assimilate the flow will be smaller. This means that the progress towards sustainability for transmaterialization and dematerialization can be measured for certain flows.

Distribution of resource use

The distribution of resource use can partially be documented by the EF. In some projects, the distribution of the EF within societies has already been calculated (Wackernagel, 1998). It is possible to reflect *intragenerational justice* of distribution of resource use within regions if the EF is calculated for different groups within society, e.g., different income groups, rather than whole regions. Even though the EF reports about the ecological capacities currently occupied, it does not document whether these spaces are actually sufficient for meeting the needs of people. *Intergenerational justice* is considered in as far as ecological deficits are identified. These deficits lead to an accumulated ecological debt burden for future generations.

Population growth

Population growth is indirectly considered since the available productive area per capita will decrease when the population grows.

CONCLUSIONS AND DISCUSSION

An essential part of sustainable development is to reduce the throughput of resources in relation to the added human value. All processes degrade the quality of energy, and more or less waste is generated. From a thermodynamic point of view, those 'bills' must be paid for through processes run by energy from outside the ecosphere. The sun-driven biogeochemical cycles of nature are essential to maintain life on earth. Therefore, most of those bills must, in the end, be paid for by productive areas receiving sunlight. Consequently, the method of footprinting, relating various throughputs of resources to the respective fertile areas required, offers an attractive possibility of auditing sustainable development.

A culture’s lifestyle, with its demands of services on the one hand, in combination with its technical and organizational skills to provide services per throughput of resources on the other, gives us the footprint of that culture. By measuring the present footprint, and then calculating the footprints for various options, more resource efficient ways of meeting human needs can be evaluated and launched. So, the EF is not only relevant for estimating the situation with regard to the areas needed to sustain us today, but also for testing different strategies for the future.

For a brief estimate of a culture's footprint, in order to assess the combination of human demands, and the technical processes to meet those demands, the already established calculation routines for the EF are sufficient. In this paper, we analyzed how the EF can be used for more comprehensive assessments of sustainability. Our results are summarized in Table 1. Some aspects are already considered in present EF calculations. Others have the potential to be considered in a way that makes it possible to measure their progress towards sustainability. Still, other aspects are very difficult, or not recommended, to include in EF analyses.

We have identified three types of aspects that should be handled in different ways by the EF method.

1. Additative aspects that should be added to the EF value.
2. Non-additative aspects that should be adjusted to avoid double counting when included in the EF value. These aspects should also be displayed separately and without adding them to the additive aspects.
3. Aspects that should not be included in the EF but should be monitored separately.

The EF should only focus on those materials and substances for which sustainable consumption rates can be provided for by the biosphere. the EF should not include materials and substances which need to be phased out completely, or almost completely. For example, emissions of persistent compounds foreign to nature. Such compounds must be accounted for separately by some other monitoring tools, complementary to the EF. This is also true for compounds for which assimilation figures are lacking and cannot be estimated. Also, since the footprint provides an overall throughput analysis, it does not give justice to many important qualitative aspects such as methods of harvesting and managing renewable resources, like slash and burn of rain forests or the killing of dolphins while catching tuna fish. Finally, since the EF only addresses ecological conditions of sustainability, most aspects of the fourth principle, like the fulfillment of basic human needs, are not addressed by the EF.

For separate aspects, it is possible to use the EF as an indicator for the progress towards sustainability, for example, the area needed to assimilate acidifying substances will decrease as the emissions of such substances decrease. It is, though, difficult to use the EF as a reliable overall indicator for progress towards sustainability when non-additive aspects are aggregated to the footprint. Most non-additive aspects will be hidden and will not affect the footprint value since the same area can be used for several non-additive aspects and the footprint method excludes double counting. The productive area needed for additive aspects may also be hidden. For example, if the area needed to assimilate emissions of copper plus built up land exceeds the productive area needed for additive aspects, changes of aspects such as carbon dioxide emissions or use of agricultural land will not affect the footprint value (unless the additive aspects become the dominating ones). In this way, the EF offers an ecological minimum criterion for sustainability while not being sensitive to all movements from, or to a more, sustainable world.

We suggest that non-additive aspects should be presented separately. Additive aspects, however, can be included in the total footprint value. Also non-additive aspect that exceed the primary footprint can be added to the footprint, see Figure 1. To display the various parts of the total EF value in this way seems a natural way of comparing various aspects of sustainability in a certain region. Consequently, the value of the EF as a tool for planning towards sustainability is increased.

One conclusion from this study is that it is fruitful to relate the results from EF calculations to a comprehensive framework of sustainability. It will help the user of the EF to see what parts of sustainability that are included in the EF analysis. Also it points to the aspects which the EF is particularly efficient at assessing, e.g., scale of flows in the human economy in relation to existing ecological areas or relevant aggregates of a variety of human impacts. Furthermore, a comprehensive framework makes it possible to identify what parts of sustainability are not covered by the EF assessment, and therefore should be considered in some other way.

The footprint is particularly effective for documenting human use or abuse of the potentially renewable functions and services of nature. Aspects that need to be monitored with other indicators and measures are activities that should be phased out completely or almost completely to obtain sustainability, and certain qualitative aspects of sustainability that are not easy or relevant to transfer to spatial measures. In other words, the EF does not cover all aspects encompassed by the systematic sustainability perspective used in this paper, but is consistent with its thrust. In addition, it offers a quantitative interpretation of central aspects of the systematic sustainability perspective and puts their more abstract criteria into a more tangible measurement. Therefore, the EF is a complementary tool to the principles for sustainability: as a yard stick for measuring the ecological bottom-line of the renewable use of the biosphere — a precondition for securing people's quality of life.

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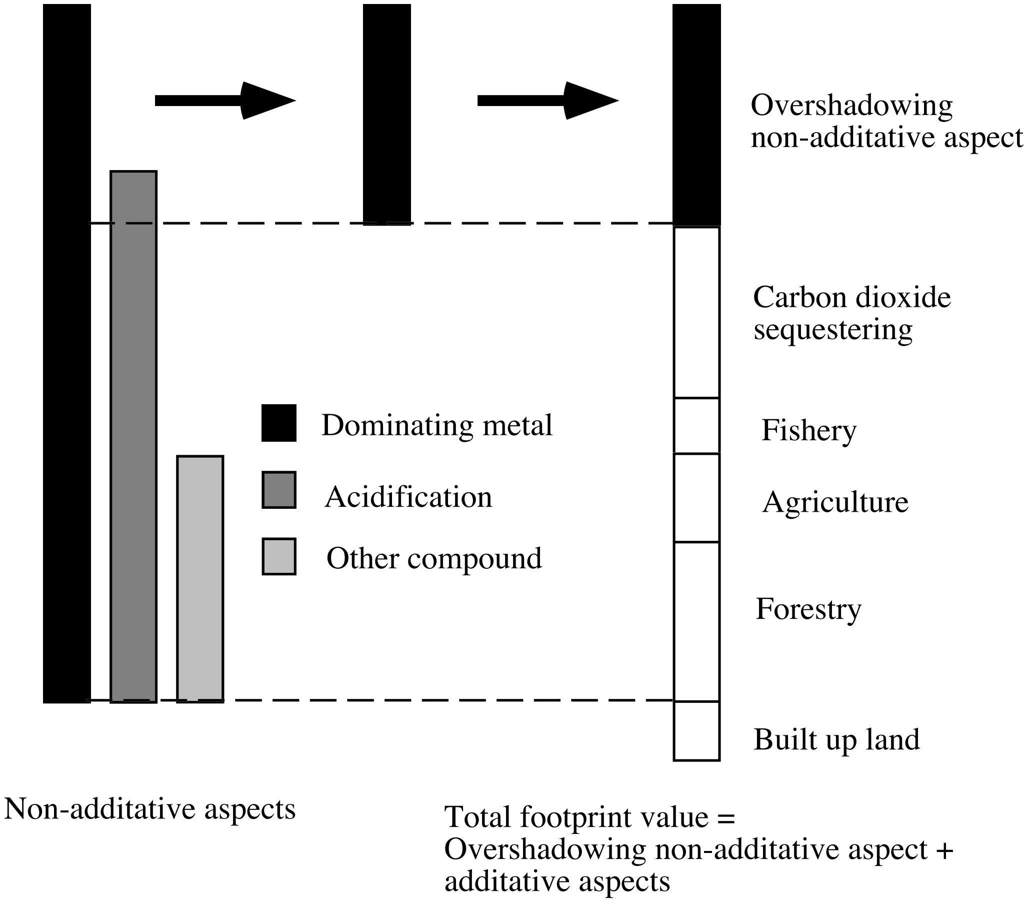

Figure 1 The presentation of additive and non-additive aspects and the total footprint value

$$\mathbf{I} = \mathbf{i} \times \mathbf{m} \times \mathbf{u} \times P$$

I = impact in nature
i = **I**/**M**; impact / material and energy flow;
m = **M**/**U**; material and energy flow / utility or service;
u = **U**/P; utility or service / capita;
P = population

Figure 2 The impact on nature is given as a product of four anthropogenic factors. Given the population and development goals in the form of a global industrialization, the means to decrease the impact on nature to a sustainable level are a de- and transmaterialization of the societal exchange of materials with nature. (There have been various combinations of factors used in this type of equation, which (at least) goes back to Ehrlich and Holdren (1971, 1972).)

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Table 1 Ecological footprint from a sustainability perspective

Aspects of sustainability	**Present EF calculations**	**Can the aspect be related to sustainability through EF?**	**Can progress towards sust. be measured for this aspect in the EF method?**
Principles 1 and 2 [1]			
Fossil fuel induced carbon dioxide	Area is calculated as the bioproductive area needed for sequestering CO_2.	Possibly, but there is no strict rationale by which consumption of fossil fuels can be related to an area.	Not in all cases. A transition from fossil fuels to biofuels can lead to a larger area using the current method.
Waste assimilation of non-synthetic substances other than carbon dioxide	Area needed for detention of nutrients. (Metals and minerals are calculated indirectly through their energy needed.)	Some, when the assimilation capacity can be estimated and it can be transformed into an area.	Yes, this is possible for the compounds that are included, see left.
Substances foreign to nature	Not included.	No since little is known about the assimilation capacity. (However, it could be assessed how much bioproductive area is lost because of long-term intoxication.)	Not included.
Principle 3 [2]			
Built up land	Yes.	Yes.	Yes.
Forestry and agriculture	The land area needed is included and usually calculated based on the current (rather than sustainable) productivity.	Some parts of lost long-term productivity and biodiversity can be included if they can be transformed into an area.	Yes, when long-term productivity and biodiversity are considered.

Fisheries	Fish catch is related to average marine production.	Yes, if types of fish species that are caught are considered.	Yes, if types of fish species that are caught are considered.
Water use	Mostly no. Some studies underway.	Partly: spatial aspects that can be included are the area needed to supply water consumption, to compensate for productivity losses, and for cleansing water.	Yes, for spatial aspects that are included, see left.
Principle 4 [3]			
Area efficiency	Overall efficiencies are included.	Yes, if specific productivity is used.	Yes, if specific productivity is used.
Transmaterialization and dematerialization	Yes indirectly, for those materials that are included.	Yes indirectly, for those materials that are included.	Yes indirectly, for those materials that are included.
Distribution of resource use	Some parts of intra-generational justice on the regional level are included. Inter-generational justice is considered in as far as ecological deficits are identified.	See left. Further, it is possible to reflect *intragenerational justice* of distribution of resource use within regions if the EF is calculated for different groups within society, e.g., different income groups, rather than whole regions.	Yes, see left.
Population growth	Indirectly, since the available productive area per capita will decrease when the population grows.	Indirectly, see left.	Indirectly, see left.

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[1] Increased concentration of substances extracted from the earth crust or produced in society.
[2] Reduced production capacity and biodiversity through manipulation and harvesting.
[3] Efficient and just use of resources to meet human needs.