FOOTPRINTS FOR SUSTAINABILITY: THE NEXT STEPS

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Abstract. The concept of an ecological footprint is based on the understanding that every individual human appropriates a share of the productive and assimilative capacity of the biosphere. An ecological footprint corresponds to this exclusive biologically productive area that a defined population uses for all its resource requirements and wastes, and is expressed in terms of bioproductive space, with world-average productivity. Humanity's footprint or its aggregate ecological demand can only temporarily exceed the productive and assimilative capacity of the biosphere without liquidating and weakening the natural capital on which humanity depends fundamentally. Therefore, accounting tools for quantifying humanity's use of nature are essential for overall assessments of human impact as well as for planning specific steps towards a sustainable future.

This paper discusses the strengths and weaknesses of the ecological footprint as an ecological accounting method, points out research needs for improvement of the analysis, and suggests potential new applications. The paper identifies ten new applications of the tool to make it applicable at various geographic scales and for a number of analytical and didactic purposes. Then nine methodological improvements are suggested that could refine the currently applied method, making assessments more sensitive to a larger number of ecological impacts. It concludes that many crucial questions pertinent to building a sustainable society can be addressed by current ecological footprint research. By making the method more complete, this tool could evolve from being largely of pedagogical use to become a strategic tool for policy analysis.

Key words: appropriated carrying capacity, ecological accounting, ecological footprint, planning tool, resource accounting, sustainability.

Abbreviations: FAO – Food and Agriculture Organization; GIS – Geographic Information System; IIASA – International Institute for Applied Systems Analysis; IPCC – Intergovernmental Panel on Climate Change; IUCN – World Conservation Union (originally International Union for Conservation of Nature); NGO – Non-Governmental Organization; OECD – Organization for Economic Cooperation and Development; UNEP – United Nations Environment Programme; UNSTAT – United Nations Statistical Division; WCED – World Commission on Environment and Development; WWF – World Wide Fund for Nature (originally World Wildlife Fund).

Introduction

The purpose of this paper is to summarize the objectives of ecological footprint analysis, to discuss the strengths and weaknesses of the method, to point out research needed for improvement of the analysis, and to suggest potential new applications.

Many resource economists (following Hotelling, 1931) maintain that resources which are not increasing in value at least as fast as prevailing interest rates should be depleted to extinction (or 'liquidated') and the revenues put into financial capital markets rather

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than sustainably harvested. To many others, however, the intentional depletion of resources is an intuitively unattractive, if not threatening, idea. Even if some individual resources might be expendable, a sustainable economy without sufficient renewable natural capital is difficult to comprehend, in spite of some historical success in substitution as scarce resources are depleted (Barnett and Morse, 1963). For example, coal and other fossil fuels have been substituted for fire wood in most of the industrialized world, and silicon, one of the most abundant elements of the Earth's crust, is now replacing the much scarcer copper in telecommunication applications, while providing even higher performance as in the case of optical cables. However, regardless of one's perspective, in order to understand an economy's resource and waste disposal constraints and to support resource policy decisions, it is essential to know to what extent the human economy is using natural capital and to what extent this use is within the capital's regenerative capacity. Without this knowledge, it is more likely that development will continue to liquidate natural capital, rather than being based on a sustainable use of such capital.

Since the publication of the Brundtland Report (WCED, 1987) which carried the sustainability discussion into governments and businesses worldwide, much effort has gone into clarifying the meaning of the sustainability concept. Most definitions that have emerged identify two interwoven aspects to the challenge: (1) an adequate quality of life for people all over the world should be secured; (2) this must not be done at the expense of using the earth's bioproductive capacity beyond its ability to regenerate.[1] We call the first aspect the socio-economic imperative and the second aspect the ecological imperative of sustainability. In clarifying these two imperatives, an essential aspect has been the search for measurement procedures that make the corresponding issues tangible, the insights applicable, and the progress accountable. Therefore, two complementary accounting tools are required:

A) *Psychological quality of life assessment methods*, for monitoring the socio-economic sustainability imperative. Even though no definite tool exists, and various aspects of quality of life may need different tools, there are a number of measures available that approximate a society or an individual's quality of life (Veenhoven, 1999). Prominent approaches are livability and social health indicator initiatives (Jacksonville, 1993; New Economics Foundation, 1995; Miringoff and Miringoff, 1999), aggregates such as the Human Development Index (UNDP Annual) or the Genuine Progress Indicator (Goodman et al. 1999), and assessments of individual well-being (Pavot et al., 1998; Myers and Diener, 1995). To develop a tool that is more focused on sustainability, Redefining Progress has embarked on a 'satisfaction barometer' initiative, which is still in an early stage of development (for more information consult the web site of the indicators program at http://www.rprogress.org). Though quality of life measures are essential for assessing sustainability, they are not covered in this paper.

B) *Biophysical assessment methods of the human appropriation of biocapacity*, for measuring the ecological imperative of sustainability. Many have developed tools for comparing human use of nature to nature's ability to regenerate. The most comprehensive attempt for measuring humanity's overall impact may well be the 'Ecological Footprint' concept, earlier also known as 'appropriated carrying capacity,' which is the subject of this paper (for a more in-depth discussion see Rees and Wackernagel, 1994, or Wackernagel and Rees, 1996). The purpose of this paper is to analyze its strengths and weaknesses and to propose steps for its further development.

Ecological footprint assessments allow researchers to analyze whether the amount of biotically productive area available to an economy is equal to or greater than that required to supply all consumed resources and to absorb all generated wastes. This precondition is necessary (although not sufficient) for sustainability. Wackernagel et al. (1999a) have shown that this precondition has not been met. The current global level of resource consumption and waste generation, to be sustainable, would require a biotically productive area greater than that of the biosphere. Furthermore, if all countries were to achieve the level of consumption characteristic of the OECD countries, the area required would be at least three times that which is available.

Apart from merely analyzing the present situation, the ecological footprint provides a framework for sustainability planning in the public and private domain. Various applied research projects have already been completed, from the global down to the local scale. At the global and national scale, some studies have compared the countries' overall consumption to their ecocapacities or analyzed the ecological capacity embodied in trade (Wackernagel et al., 1997; 1999a). At the municipal scale, local footprints are measured against the national average, and sustainability strategies are evaluated with the footprint tool (Wackernagel, 1998; Davidson and Robb, 1994). At the household scale, the individual impact is assessed through direct accounting or simplified questionnaires,[2] and at the products level the ecological demands of competing management and process options or the cumulative effect of consumer items are compared (Wada, 1993; Kautsky et al., 1997; Folke et al., 1998). Such ecological accounts can help policy planners assess a population's ecological impact and compare this impact to nature's capacity to regenerate. Still, since the ecological footprint is a tool in development, some aspects are not yet included or some data needs to be improved for more detailed analysis. Therefore, the purpose of this paper is to identify the research tasks necessary to strengthen current ecological footprint applications and to outline the potential of new applications for this more refined ecological footprint method.

This paper builds on two encouraging conclusions which underline the necessity and usefulness of more advanced ecological footprint research. First, it is possible to define sustainability simply and clearly. There are ways to measure how far current practice is from reaching the ecological (bottom-line) imperative for sustainability. The ecological footprint builds on a series of other tools and assessment approaches such as net primary production accounting (Lieth and Whittaker, 1975; Vitousek et al., 1986; Fischer-Kowalski et al., 1997), energy and Emergy accounting (Odum, 1996; Costanza, 1980; Hall et al., 1986), regional or industrial metabolism studies (Ayres and Simmonis, 1995; Baccini and Bader, 1996; Lowe et al., 1998), carrying capacity assessments[3] or life cycle analysis (Abel et al., 1990). Since we can measure progress, it therefore becomes more evident how far humanity needs to go in order to reach ecological sustainability.

Secondly, as many others have pointed out (Meadows et al., 1992; Brown et al., 1985–1999), and as we have also documented elsewhere in aggregate terms (Wackernagel et al., 1999a), humanity as a whole must reduce its resource throughput in order to achieve sustainability. However, the other encouraging insight is that there is evidence that a reduction in resource throughput (as measured by the ecological footprint) need not require unreasonable sacrifice; in fact, it is feasible even to *improve* the quality of life while reducing one's footprint. While a reduction in footprint does not *necessarily* improve quality of life, there are many informative examples at the individual and societal level showing relatively high quality of life at low footprints[4] as well as significantly improved quality of life at significantly reduced footprints (Dominguez and Robin, 1992). These examples not only emphasize that sustainability is possible, but also become case studies teaching important lessons. With more refined ecological footprint methodology, these case studies can be analyzed in more detail and richer conclusions can be drawn.

State-of-the-art of current ecological footprint research

The ecological footprint is based on the understanding that, to varying degrees, every person uses, or appropriates, the productive and assimilative capacity of nature. Therefore, we can also refer to the ecological footprint as 'appropriated carrying capacity.'[5] As long as the total human load (individual use summed over all individuals) stays within the ecological capacity of the biosphere, this human use of nature is sustainable. The essence of sustainability, therefore, is to estimate to what extent it does. The 'ecological footprint' is an estimate of how much of nature's productive and assimilative capacity people use to supply their current resource use and to assimilate the waste production associated with that resource use. Ecological footprint calculations are based on two simple assumptions; first, that we can keep track of most of the resources we use and many of the wastes we generate; secondly, that most of these resource and waste flows can be converted to a corresponding biotically productive area. Thus, the ecological footprint of any defined population (from a single individual to a whole city or country) is the area of biotically productive land and water appropriated exclusively to produce the resources used and to assimilate the wastes generated by that population, using prevailing technology. In today's globalized economy, most people use resources and assimilative capacity from all over the world. Footprints sum up these ecological areas without regard to where that land and water surface area may be located on the planet. To use a common unit of measurement in all our ecological footprint applications, we express our results in terms of bioproductive space with world-average productivity. We do this not only for the footprints, but also for the bioproductive areas available in a region, a nation or a watershed. By using one common unit, all results become directly comparable to each other all over the globe. At the same time the overall productivity of the planet is not distorted. The global capacity, unadjusted or expressed in bioproductive space with world-average productivity will show up in both cases with exactly the same area.

The newest estimates for the year 1995, which are based on published United Nations statistics (Wackernagel et al., 1999c), show that an average Canadian required 7.2 ha of biotically productive land and marine surface area to provide for his or her current level of consumption. These 7.2 ha, or 0.072 km^2 to express it in more visible terms, correspond to an area of 18 US football fields combined.[6] In comparison, an average US citizen lived on a footprint about 30 percent larger (10 ha), an average Italian on a little above 4 ha. An average Swiss or German appropriated close to 5 ha. Since the study assumes for the calculations that current yields can be maintained forever (which is optimistic) and does not yet include all uses of nature, these figures underestimate the biologically productive areas truly necessary to sustain the current lifestyle of these people.

This 'demand' for ecological capacity can now be compared to the biosphere's 'supply' of ecocapacity. Dividing all the biologically productive land and sea on this planet by the 1995 global human population results in an average of 2.2 ha per person (Wackernagel et al., 1999a).[7] This is less than half of what is necessary to accommodate the footprint of an average Swiss. Of these 2.2 ha per person, 1.7 are land-based natural and managed ecosystems such as forests, pastures and arable land, and 0.5 ha are ecologically productive ocean surface areas, most of which are located above continental shelves.

Current methodological limits and recent improvements

Because the purpose of the footprint model is to provide a graphic way of determining and visualizing by what order of magnitude human consumption is currently exceeding the biosphere's regenerative capacity, it may appear to be overly simplistic, utilitarian and fragmentary. It could legitimately be criticized as simplistic in the way it summarizes human impact in one figure, as utilitarian in the way it represents nature as a collection of resources and waste sinks, and as fragmentary in the way it separates ecological functions. It also ignores some systemic ecological services, such as the maintenance of water cycles, the stabilization of atmospheric composition, the provision of pollination services or the offering of spiritual and aesthetic inspiration. Nevertheless, the tool allows people with different perspectives to start their discussion from some common ground and basic consensus on how the world operates. Therefore, the footprint does not claim to be a precise estimate of human impact; rather, it intentionally errs on the low side of the human use of ecological space.

This is an important feature of the method. It means that the footprint measure is less careful than the precautionary principle since it systematically underestimates human use of ecological capacity. In other words, it is a minimum requirement for ecological sustainability. This is not to challenge the precautionary principle. On the contrary, it helps to show that current footprint estimates document an ecological crisis even if there were no need to leave any margin for possible error or reserve any carrying capacity for unforeseen requirements. Even by using this mechanistic ecological accounting, footprint accounts can document that humanity's aggregate resource demand and waste production are overshooting the biosphere's capacity thereby foreclosing options for the future.

Still, some critics have claimed that footprint accounts exaggerate the ecological impact of humanity since the accounts include, to use their words, 'hypothetical land', particularly for the absorption of CO_2 or other waste products. We disagree that ecological capacity for waste absorption is less 'real' than that for resource production. We may not see CO_2 and other waste streams; we may not even have to pay for releasing these wastes. Nevertheless they are a material reality – and require ecological space to be turned back into resources.

If the total footprint size for resources and waste put together ends up being larger than the biocapacity that exists, this points only to the very real existence of overshoot. In the case of fossil fuel, the footprint indicates that humanity is generating more CO_2 than can be absorbed by the surface area the earth offers. The assertion here is not that there is more land than exists, but that humans are consuming resources at a rate that would require more land than actually exists. We feel that measuring the spatial impact of fossil fuel by accounting only for its waste, through areas needed to absorb the released CO_2, provides a robust underestimate of its overall effects (Wackernagel and Rees, 1996: pp. 71–74). Moreover, we admit that planting trees, the current prevailing method of sequestering fossil fuel generated CO_2, can only be a temporary solution and that there may be cheaper and less space-intensive methods. Again, this is an example of the very kind of option the footprint is intended to reveal. Better sequestration technology does indeed have great potential for reducing footprints. And so does energy conservation and ecoefficient energy production. This is precisely the kind of scenario and insight we hope the footprint stimulates, and identifying such options is one of the follow-up initiatives we would like to encourage, as discussed below.

While the ecological footprint includes a broad range of human impacts, nevertheless it is consistent with basic thermodynamic principles such as the law of mass conservation and the first two laws of thermodynamics. In contrast to many sustainability measures that add up various issues using arbitrary weighting mechanisms (e.g., the consumption pressure index of the global living campaign, WWF, 1998), the aggregation of a variety of human impacts incorporated in the ecological footprint is the sum of the mutually exclusive areas appropriated by these human activities. Therefore, the total represents a meaningful whole – not just a compilation of index points. Also, the footprint provides some illustration of the connections between various ecological functions. It documents their competition for ecological space: various pressures on nature, such as biodiversity loss, erosion, water scarcity, CO_2 accumulation, etc., can increase the pressure on each other, or one ecological impact can exacerbate another one (e.g., deforestation decreases an area's humidity, or fish farming appropriates arable land for feed production).

In most footprint assessments, we use official data from national or international para-governmental or governmental organizations[8] – not because it is necessarily the most reliable that is available, but so that responsibility for accuracy can be attributed and to show that official data, interpreted from an ecological perspective, can yield significant new conclusions. In essence, footprints, with quite simple accounting procedures, make visible what most people do not perceive in their everyday lives.

Some significant ecological impacts of human activities are still missing in current footprint accounts. Probably the most significant ones involve waste assimilation, such as area required to process degradable substances. The principal waste assimilation component of the ecological footprint currently is the land area required to assimilate carbon dioxide formed by fossil fuel combustion, or in some applications, plant nutrient loads from industrial agriculture (Wackernagel et al., 1999b) or human waste (Folke et al., 1997). Other aspects such as domestic solid waste or most of the industrial wastes are still neglected. This omission underestimates, particularly, the footprint associated with mineral and metallic resource use. Their use can cause sizable ecological impacts, particularly through the release of toxic materials in mining and processing. Persistent (i.e., non-degradable) products and toxic wastes, however, will never be included in footprint accounts because there is no reasonable assimilation rate within human time scales that would allow the continuous use of these substances without an increase of their concentration in the biosphere. Therefore, they cannot be part of a sustainable world and need to be monitored separately.

Particularly in arid areas, the withdrawal of fresh water can directly compromise the biocapacity of the land from which the water is taken. This use of such water, therefore, leads to additional footprint areas that correspond to the additional bioproductive area necessary to compensate for this loss of bioproductivity. These additional footprints are not included in the current footprint accounts. The reason is that the availability of internationally comparative and ecologically meaningful water data is limited. Since water in arid areas has become a limiting factor, research is needed to develop methodologies to calculate approximations of such water footprints. Some preliminary research of possible methodologies has been started at the Center for Sustainability Studies (Callejas, 1999).

More realistic assessments also would need better data on sustainable yields; not only for crops, but also for forests, aquifers and the waste absorbing functions of nature. For the lack of better data, we assume current reported industrial yields are sustainable, whereas they probably are not. This is an additional reason why our estimates are an underestimate of humanity's carrying capacity overshoot.

Another human impact that is still weak in footprint accounts is the loss of biodiversity. In present estimates we allocated 12 percent of the bioproductive area for biodiversity, following the politically courageous but ecologically insufficient suggestion by the Brundtland Report *Our Common Future* (WCED, 1987). This allocation is a reminder that not all the biosphere's productive capacity is available for human use. Most conservation biologists would argue that allowing 12 percent for protected space is insufficient for securing biodiversity worldwide (Noss and Cooperrider, 1994). However, in some areas a 12 percent set-aside may be more than sufficient to protect what is left. For example, in some intensively used areas such as central Europe, or the millennia old monocultures in Southern China, where much biodiversity has already been lost, 12 percent may be adequate, if not generous, to secure the surviving biodiversity. In less impacted areas such as the Amazon forest, however, human pressure on biodiversity may lead to significant losses even with considerably larger protected areas. These areas harbor a large percentage of the 30 million other species inhabiting the planet. Most of them cannot coexist in the spaces occupied so intensively for human purposes. In fact, many are systematically excluded. Agriculture calls any species that is not exploitable a 'weed', and through urbanization, much of the most fertile land is just paved over. The question therefore becomes, how much of the bioproductive area should be left relatively untouched for these other 30 million species. In our experience, when asked how much of the earth's productive area should be appropriated for human use, only a few people, scientists and non-scientists alike, feel that humanity should appropriate more than two-thirds in order not to compromise the long-term stability of the biosphere.

However, to be even more generous to the human species and make sure that our analysis does not exaggerate the ecological scarcity of today, we continue to use the 12 percent suggestion from the Brundtland Report. Using this (probably) far too conservative number, the available bioproductive space per person shrinks from 2.2 to below 2 ha. With the anticipated global population of 10 billion for the year 2050 or before, the available area will be reduced to 1.2 ha, including the sea area. Already, the average Italian, for example uses 120 percent more than what is available for the average world citizen, or over 180 percent more than is at hand per Italian within their national territory. Worldwide, humanity's footprint of 2.3 ha per person significantly exceeds the eco-capacity of the biosphere. If we put aside 12 percent for other species, then the overshoot is 30 percent. In other words, humanity currently consumes more than nature can regenerate and is depleting the earth's natural capital stock. Therefore, in order to clarify in more detail how much capacity is necessary for meaningful biodiversity preservation, it is essential to get a more realistic estimate of the available biocapacity on this planet.

Limitations of the method not only can be found in respect to the assessment of the ecological impacts but also in the allocation of these impacts among countries or regions. A prominent example of this misallocation in our current calculations is international tourism which may well correspond to approximately 10 percent of the world's resource consumption.[9] For example, consider that an Italian going to Mexico on holidays would leave some footprint in Italy for the take-off, some possibly in the US when changing airplanes, and in Mexico for the last stretch of the airplane ride and for the hotel use and other recreational activities. However, this entire tourism footprint should be charged to Italy's footprint account. Since the flow of tourism from the north to the south is exceeding the tourism in the opposite direction, present footprint calculations underestimate the difference between the average footprint size in the north and in the south.

To overcome some of the above weaknesses and to strengthen the methodology, the footprint calculation procedure has been refined. Since the research presented in Wackernagel and Rees (1996), we have introduced a variety of new features such as a more complete and standardized accounting of human consumption making sure all major consumption categories are covered in our accounts, particularly for the national accounts. As reported above, we have advanced our accounts by using for both footprints and biocapacity assessments a better defined and more meaningful measurement unit, which we call 'hectares of bioproductive space with world-average productivity'. This measurement unit allows us to compare all results worldwide. Standardizing the measurement unit depended on two innovations: the yield and equivalence factors. Yield factors compare the productivity of an ecosystem category in a nation to the worldwide-average productivity of the same ecosystem category. For example, it shows the difference of potato yield per hectare in France as compared to the average potato yield worldwide. The equivalence factor shows how much more productive a particular ecosystem category is as compared to average bioproductive space. For example, we found that typical forest ecosystems are 1.2 times as productive as average bioproductive space. Once these two factors are determined, each nation's ecological space they use in terms of footprint, or have available in their country in terms of biocapacity, can be translated in the common measurement unit.

Further, in contrast to the earlier estimates, present assessments include the use of oceans for fishing, and some land and sea area to protect biodiversity. Although this complicates the assessment slightly, it makes it also more complete and provides more realistic assessments of the overall consumption and ecological possibilities of nations such as Iceland that heavily depend on fisheries.[10] With the increased international attention to carbon emissions, we are now distinguishing between solid, liquid and gaseous fossil fuel consumption, taking account of their specific carbon intensities. CO_2 absorption estimates and forest yield data have been harmonized using IPCC statistics.

By using this advanced methodology, assessments of nations have become far more robust. In addition, by mainly using national government statistics, supplemented with statistics from the United Nations Statistical Division (UNSTAT), the United Nations Food and Agriculture Organization (FAO) and the Intergovernmental Panel on Climate Change (IPCC), we show what the ecological picture looks like, if we take government data at face value.

Potential for new and more sophisticated applications

In spite of the methodological shortcomings and omissions that limit current footprint assessments, they are useful for educational purposes and for presenting an estimate (in fact, an underestimate) of the earth's human carrying capacity (i.e., the human load in relation to the ecological capacity required to support that load). Footprint estimates are not only useful at the global level, but are the most complete natural capital accounts at the national level available today. No government institution is measuring, in any systematic way, how much natural capital their country has as compared to their level of resource consumption and waste production. One apprehension of governments may be that footprint accounts are not dependable since they lack detail and robustness. And indeed, a longer time series and a wider tested methodology will make footprint results more dependable and less contestable. However, research to overcome some of the limitations would not only make the existing applications more accurate and robust, it would also open doors to more meaningful and sophisticated applications.

Therefore, before discussing research gaps and possibilities for methodological improvements, we outline ideas for new generations of ecological footprint assessments that would come in reach with a more tested and detailed assessment framework and with more reliable and complete data.

1. Making existing calculations accessible. A first step is to increase the value of existing applications, not only by making them more refined, but even more by making them more accessible and the method more transparent to other researchers. To increase researchers' knowledge and understanding of the more advanced footprint studies that already exist, the calculations need first of all to be documented in more detail.Although the calculations have been kept as simple and clear as possible, and are presented in spreadsheets, many details are not sufficiently well explained such that they can be easily replicated. Also, certain assumptions or generalizations that are necessary in some areas of the calculation due to weak data sources would need a more detailed description and discussion of the calculation's limitations. Better documented calculations would also lead to simpler and more logical presentations of the current calculation and lower the acceptance threshold for research colleagues to apply the method to their research projects. Further, the existing results become more transparent and reproducible, weaknesses and limitations more obvious and the necessity and validity of footprint studies more apparent.

2. Developing manuals for new assessments at the regional and local level. Many municipalities or environmental NGOs have been interested in developing footprint assessments of their region, but remain discouraged since there are no practical 'how to' resources available for guiding novices through the process of an assessment. Manuals (adapted for each country) could be assembled that contain most of the generic data necessary for the calculation, references to data sources for specific information, and guidance on how to find (or measure) local data. Also, the manual would offer an easy-to-follow procedure in both electronic and printed format that guides the calculation step by step. For reference and as a benchmark to calibrate the local assessment, an annotated version of the national assessment would be included in the manual.

3. Establishing a comprehensive account of national and regional biocapacity. To get a more comprehensive sense of the natural capital assets of a country, a comprehensive inventory of ecological capacities within each country would first need to be established. Essentially, this would require a land-use inventory in categories as detailed as possible. For each identified category or area, a yield factor would need to be estimated which describes the bioproductive potential of each area as compared to the world-average productivity. Such an inventory may become even more flexible to support assessments at all geographical scales if it is integrated with a GIS. Given such a comprehensive inventory, more detailed studies would enable inclusion of ecological functions such as waste absorption and water use which are specific to local circumstances and which are hard to quantify at the national level. Since much of the land-use and productivity data may already be collected by government agencies or specialized research institutes, the project could produce rapidly, and at moderate costs, some fundamental insights into the country's ecological capacity. Also, such assessments would enable the tracking of the change in a country's ecological capacity over time and document the nation's potential domestic ecological 'supply' and its distribution over the nation's landscape.

4. Establishing comprehensive accounts of national and regional loads. Since nations track trade flows and economic production, this scale offers the most complete data set for analyzing the resource throughput of a society. The waste output side is not as completely documented. Some of the missing data can be extrapolated from the resource inputs, since all inputs eventually become waste. For many of the resource and waste flows the ecological capacities needed to sustain them are known (at least in first approximations) which allows one to attribute corresponding bioproductive areas to these flows. Aggregating these areas would show the nation's 'demand' on the biosphere. Accounts in different years would provide a time series of snapshots of the nation's human load.

Connecting the biocapacity assessment (as discussed in 3, of this section) with this consumption analysis allows one to directly compare the available ecological potential within the nation (or on the globe) to the ecological demand of the people living in the nation. Not only does such an analysis give the population a more realistic illustration of the effects of their lifestyles; even more importantly, it provides a quantitative assessment of an essential national asset that can enhance a nation's future competitiveness (Sturm et al., 2000).

5. Comparing the 'consumption' footprints and 'production' footprints. The ecological footprint shows how much biological capacity is necessary to supply a population's household consumption of natural resources and to assimilate its waste generation (a more precise name of the footprint would, therefore, be the 'ecological footprint of consumption'). Analyzing the footprint from this perspective is the most relevant since it links environmental impacts to people's consumer decisions. After all, much of what is produced follows a consumer demand – or at least there are consumers willing to purchase the products even if the demand was artificially created.

Obviously, a different lens could be taken. Rather than attributing environmental impacts to the final consumer, it could as well be associated with the producers of the products and services. This ecological load of economic production can be documented as well, and we could call it the 'ecological footprint of production'. This latter footprint would document the biological capacity necessary to keep this population's economic production running. More specifically, the production footprint corresponds to the ecological functions and services required to generate the population's income. This income, in return, will pay for the population's consumption.

Obviously, the footprint of production is not an additional footprint, but rather an impact analysis that organizes the environmental impacts from the production rather than the consumption perspective. For the globe (or humanity) as a whole, the consumption footprint will be identical to the production footprint since there is no trade with other planets and, therefore, essentially everything produced on the planet will eventually be consumed on the planet (what is not consumed can be considered to be waste associated with the consumed goods). For any subsection such as a nation, a region or a household, however, the consumption and the production footprint do not have to balance out. To illustrate, consider the example of an industrialized farm that sells all its products to the market. All the fields, plus the footprint for the resource inputs such as tractor fuel and fertilizers to work and harvest them, correspond to the farmer family's production footprint – the biological capacity necessary to sustain their income. Their consumption footprint, however, would correspond to their private garden with their home grown vegetables plus the area required to generate all the food, furniture, medical bills and other consumption goods and services that they buy. Similarly, resource-exporting regions may give up significant amounts of biological capacity while receiving little capacity in return via imported products. This becomes manifested in the discrepancy between a population's or region's consumption footprint and its production footprint. Or vice versa, a region could be a net-importer with a positive ecological trade balance as shown in Figure 1. The domestic production of this region becomes part of its consumption footprint, while its exports become part of another region's consumption footprint.

Such 'ecological leakages' or 'gains' through trade could become a valuable insight into the region's dynamic, not only for economic development strategies, but also for checking

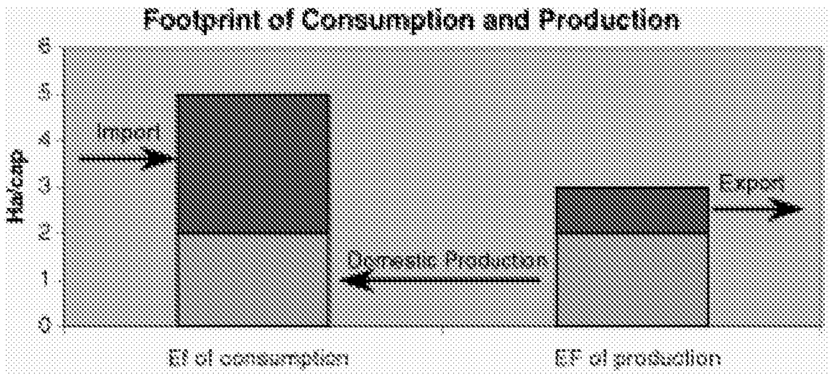

Figure 1. A hypothetical example of a footprint of consumption and of production. While the worldwide footprint of consumption and that of production are one and the same (since everything produced is eventually consumed), countries can have large ecological trade surpluses or deficits. Some of the domestic production of a country is consumed domestically while some is exported. The consumption footprint is the sum of the production for the domestic market plus the imports. Countries that have a more service-oriented economy will have footprints for consumption that exceed their production footprints.

the success of sustainability strategies. It helps to distinguish to what extent a region is truly becoming sustainable as compared to just exporting its ecological burdens while still living on a high consumption footprint. Also, such studies could illuminate to what extent the local region is ecologically endowed with sufficient capacity to meet local needs and what kind of economic development would both meet ecological constraints and human necessities, thereby promoting a stable and viable long-term economy in the region.

6. Relating regional human carrying capacity deficit or surplus to traditional measures of ecological integrity. Watershed or ecoregional (Omernick, 1987) assessments start from an inventory of the ecologically productive area in the watershed or ecoregion. Where ecoregion designations are available, ecoregional assessments have the advantage of relatively uniform ecological productivity throughout the region. In fact, this is one of the distinguishing characteristics of ecoregions. With GIS, the dimensions of all the ecologically productive area categories can be captured and their respective productivities and uses registered. Such a survey would provide an estimate of the local ecological capacity – the supply side. The demand side, that is the footprint of the local population, can be documented with various degrees of precision. Given an estimated per-capita demand for ecosystem services, and the productivity of the ecoregional categories in a watershed or other region, an approximation of the human carrying capacity deficit or reserve of the region could, in principle, be obtained. If comparable watershed or ecoregional assessments were conducted over a gradient of ecological capacity and of human population footprint, it may even be possible to correlate carrying capacity deficits with more traditional indicators of ecological integrity and identify to what extent wealthy regions are able to export their environmental impacts.

7. Developing footprint methods as measuring sticks for comparing options and choices. Rather than merely applying the footprint analysis at various geographic scales, this tool could also be used to scrutinize the ecological sustainability of processes and projects. Possible human activities that lend themselves to such analyses include:

- *Technologies and industrial production processes:* there are several paths to Rome – and several ways to provide a given service such as heat, food, information or security. Not all of these ways, however, are equally sustainable. For those services that are furnished by industrial products, footprints can contrast the ecological demand of delivering such a product using various competing management and manufacturing options. Since energy consumption is such an essential and pervasive aspect of industrial production, it would be of particular interest to compare the available array of energy systems that can provide the energy flows, covering the entire spectrum from renewable to non-renewable options. Another fundamental analysis would include a comparison of ecoefficiency in agricultural systems. Existing examples of such studies include the case of hydroponic tomatoes grown in British Columbia (Wada, 1993), aquaculture in the Baltic Sea (Kautsky et al., 1997), or packaging systems (Best Foot Forward, 1999). Further, the now quite widely performed life cycle analysis of products could be interpreted from a footprint perspective. This would not only make the results easier to communicate, but also allow people to relate this ecological demand documented by the life cycle analysis to the biosphere's regenerative capacity. Such studies would open opportunities for developing ecolabels that provide information on the cumulative effect of consumption.
- *Businesses:* many managers of business operations know about financial flows but have little if any understanding of the biophysical aspects of their organization. Even though they may want to manage for less ecological impact, they do not have the needed tools. The ecological footprint could help to interpret the metabolic flows through businesses. One could then determine the marginal economic cost or benefit of a marginal change in ecological footprint. One way of interpreting the result would be to extrapolate the business practice to the World's Gross Economic Product. This answers the question of how many planets would be necessary if all economic activities had the same footprint per dollar as that of the analyzed business. A further application could be the development of footprint-based ecolabels as suggested in earlier studies (Wackernagel and Rees, 1996).
- *Policy scenarios of development:* ecological footprints offer a way to interpret the ecological impact of policy scenarios. Such scenarios could be computer-generated, developed through discussions in workshops or assembled in political forums. Also, they could be of a local, national or global nature. For each scenario, ecological footprint accounts could allow one to determine if humanity's footprint would decrease or increase. As an alternative to analyzing hypothetical scenarios, the same method could also be applied to tangible issues such as a municipal budget or a city's economic development strategy.
- *Population and consumption:* playing population against consumption is often used as a strategy to address none of them – the costs being borne by future generations. Indeed, population growth may not be the cause of unsustainable development patterns

in low-income countries (more likely it is its result; Abernethy, 1996), but a larger population size certainly narrows options in a world that is ecologically overloaded by our species' aggregate consumption. Reducing human per capita consumption in developed countries also is a necessary condition for moving towards sustainability. As human carrying capacity always involves the combination of population size and per-capita consumption, ecological footprint studies can help to bring population and consumption together and look at the overall impact of population and consumption strategies.

- *Urban design options:* urban design has a significant impact on people's consuming behavior. It influences not only how they shop, but also how they move around, what kind of houses they live in and what kind of urban infrastructure services they require. Hence, ecological footprints offer a powerful tool for comparing the ecological demand of design options such as housing densities, transportation systems or infrastructure development.
- *Time series snapshots:* as footprints are computed over a period of several years, biophysical trends and their relationship to other developments (such as economic expansion, population growth, biodiversity loss, etc.) can be illustrated. Also, such historical trend analysis can point to expected developments and pressures in the future.

8. Building a common footprint accounting standard. A more ambitious project is to advance the ecological footprint method to a level where it could be considered a counter-piece to the System of National Accounts that produces the Gross National Product (GNP) or Gross Domestic Product (GDP). Once the calculation procedure is well defined, the results would become more replicable and comparable over time. Such an ecological–economic accounting tool could serve, in a manner comparable to GDP, as a framework for national natural capital accounting and provide the basis for a number of comprehensive national sustainability indicators.

9. Testing popular assumptions about sustainability. The sustainability debate and, more specifically, the ecological economic debate are immersed in a number of assumptions that can actually be tested empirically with tools such as the ecological footprint. Issues and propositions include: the role of efficiency gains in reducing resource consumption; the link between income and ecological impact in general and the ecological impact of poverty in particular; the level of dematerialization of economies – in other words, the extent to which the human enterprise secures its needs on a lower resource throughput; the ecological trade balances in the global economy; the validity of the Kutznets Curve for explaining the link between population health and resource throughput; the contribution of consumption, population size and population growth to humanity's global ecological load; the level of overshoot and rate of natural capital depletion; the relation between economic and ecological debt; and the gain potential of sustainable design options in architecture, city and transportation planning, industrial production or agriculture. Another area where the footprint can offer an empirical tool is an analysis of the cost of inaction. For example, it could help to identify the embodied ecological capacity necessary for the transition to a solar economy and stabilization of the atmospheric CO_2 concentration. Or it could identify the foreclosing options and increasing constraints for choice as natural capital gets further depleted. Opening these issues for quantitative analysis will help to bring more empirical rigor and a stronger scientific base into ecological economics studies.

10. Developing and compiling footprint-based educational and planning tools for sustainability. Even the best analyses are ineffective if they cannot be communicated clearly to a variety of audiences. Therefore, developing educational tools and designing simple activities to illustrate the main aspects of the analysis is essential for promoting thinking and action consistent with this empirically-based sustainability approach. Particularly in schools, from younger years up to university education, footprints are not only useful as an additional approach to look at human–biosphere interaction but can also be an integrative forum for a number of issues in both science and the humanities.[11] Obviously, this is not limited to formal education alone. Since the ecological footprint helps to translate abstract ideas into visual objects and physical realities, it lends itself to all kinds of potential exhibits, outdoor activities and games that can build on the footprint analysis. Also, its many ways of illustrating make ecological constraints accessible and generate enthusiasm for action.

As explained above, there is an average of only 2.1 biologically productive hectares per person on the globe. And assuming that setting aside 12 percent of the total area will suffice to secure biodiversity, the per-capita availability decreases to 2 ha. Population growth and ecological deterioration are reducing this area even more. The most crucial question for a sustainable world, therefore, is: how to secure an attractive quality of life out of less than 2 ha per person. Experiments and case studies are required to highlight this question and show how one can best live within these limits. A tangible application of this question may be an international, national or local competition on examples of the best ways of living on less than 2 ha. In preparation for a world population of 9 billion by the middle of the 21st century, we may even want to look for examples of high quality of life on less than 1 ha per person. For such educational ventures, the ecological footprint provides an effective tool, both to analyze and measure, and also to visualize, plan and act.

Research needs for supporting the new applications

Simple versions of this new generation of ecological footprint applications could already be developed by building on the existing assessment method. However, these applications would become more comprehensive and reliable if a number of methodological improvements and data gaps were first addressed.

1. Clarify the similarities between the footprint and other theoretical and applied approaches for expressing human ecosystem load on an area basis. Reviewers of this paper have commented that the ecological footprint is conceptually related to several other approaches that have already been used – e.g., embodied energy and Emergy. We agree, and in fact have acknowledged the indebtedness of the ecological footprint to previous work (e.g., Wackernagel et al., 1999b). For example, some researchers claim that both embodied energy and Emergy assessments can be converted into numerical values of space equivalents, providing another venue for calculating ecological footprints.[12] We recognize that other approaches are possible, and encourage further research to clarify similarities and difference of the various existing and emerging methods, not least to test and strengthen our current accounts.

2. Include natural capital depletion. In current applications, studies only document existing natural capital and its regeneration rate, expressed in terms of area. They do not say anything about the remaining stock. Since current use of natural capital often exceeds its regeneration rate, a depletion of natural capital results. Therefore, more explicit attention should be given in footprint studies to documenting the impact of this overuse. For example, in a variety of natural capital categories such as fisheries, forests, soils, water, etc., the depletion rate of natural capital should be analyzed, and the impact of this depletion on future productivity should be assessed. This would also clarify the long-term capacity potential, help to estimate how long overshoot can be maintained, and estimate how much time is available for the sustainability transformation.

3. Add more aspects to the waste assimilation side of the footprint model. Since it is hard to find reliable and internationally comparable data on the waste produced by the human economy, and since waste assimilation capacity varies so widely for different waste types and local ecological context and is measured in so many different ways, the footprint of waste assimilation has not been as adequately integrated into the overall accounts as has the consumption footprint. To overcome this obstacle, research should be conducted on:

a) How much productive area has already been lost or is occupied due to persistent toxification in the US or the world (particularly through industrial use, military training and war, and mining operations).
b) How much areal capacity is necessary for absorbing biodegradable wastes. In particular, footprint accounts would be strengthened once it were clear how much areal capacity is necessary to absorb dominant airborne contaminants such as SO_x and NO_x.
c) What is the spatial impact of solid waste disposal such as land fills. Such an analysis should include the greenhouse potential of the released methane and the ecological damage of present and future run-offs.
d) To what extent recycling, including re-circulation of process water and heat, secondary uses of raw materials, and re-processing of post-consumer waste, does, or could, reduce the ecological footprint.

4. Use GIS technology to provide a spatially more flexible and refined capacity analysis. In existing footprint analyses, the potential benefits of using GIS have not yet been exploited. Such technology would be an ideal tool for much more detailed and flexible analysis of ecological productivity, bioactivity and assimilative capacities. It would allow simple mapping, flexibility for scenario analysis and much finer resolution. Also, it would help to provide analyses at different scales and offer a spatial context in which to organize all the information relevant to ecological footprint accounting.

Such assessments could become the base for national or global carrying capacity assessments. They could incorporate more sophisticated analyses of current forest use and of arable land loss due to former and present urbanization. Historical analyses, going back many centuries, could highlight the dynamics of the decline (or regeneration) of natural capital. Case studies, such as the loss of bio-capacity in the Middle East, California or many parts of Mexico, could show the dramatic decline of biological productivity caused by human impact.

5. Base calculations on sustainable yields rather than industrial yields. For lack of better data, current footprint studies take the optimistic view that current agricultural (and agro-forestry) yields can be maintained over long time frames. There is much evidence, however, that this is too optimistic: first, industrial agricultural inputs themselves have footprints, and some of these inputs (such as phosphate fertilizers) may become scarcer and have to be taken from more contaminated stocks (leading, for example, to higher levels of cadmium in the phosphate used in agriculture and resulting in cadmium build-up in agricultural soils and finally in human tissues); secondly, the agricultural long-term capacity of the soils is systematically diminished in many areas because of soil erosion, salination, and leaching of nutrients. A comprehensive survey of the agroecological literature would be an initial step to identify more realistic assessments of the true ecological productivity. Another complementary research approach could be to develop proxy calculations of how long it would take for these ecological capacities to regenerate or, alternatively, of the resource input necessary to secure ecological regeneration. An example of the latter may be the use of green manure to compensate for the loss of soil fertility due to agro-industrial use.

With these adjusted long-term yields, assessments of footprints and biocapacity would both become more realistic, documenting a larger part of the ecological deficit of regions than current assessments.

6. Assess the biophysical costs of ecological capacity losses. We define ecological capacity as the bioproductive area multiplied by its bioproductivity. Such capacity can be lost by losing surface or damaging its productivity – or gained by restoring it. As ecological capacity is lost, the analysis of the ecological and economic cost of restoring lost capacity and of generating new capacity would provide useful information to policy makers. Questions that could be addressed include: how feasible and costly is reforestation in agriculturally marginal areas and aforestation in arid lands. What are the ecological and economic costs of technological solutions to expand production such as agriculture on floating oceanic islands or irrigation of deserts? Or can we outgrow demands by putting farms on the moon?[13] Such insights could help to identify the true cost to humanity of losing ecological capacity and to explore the viability of technological fixes to address ecological scarcity.

7. Establish a broader database on the embodied energy and resource consumption of industrial processes. Ecological footprint studies draw on a variety of bodies of knowledge and a wide array of data sources. Therefore, a systematic gathering of relevant data would make the calculations more robust, would help to identify current weaknesses and would enable a larger variety of scenarios to be developed. Particular focus is needed on updated data describing embodied energy and resources of processes and products, such as the data bases compiled by the Division for Material Flows of the Wuppertal Institute for Climate, Environment and Energy; Jørgen Nørgard and his team at the Technical University of Denmark; Patrick Hofstetter at the Swiss Federal Institute of Technology, or Henk Moll and his colleagues at the Center for Energy and Environmental Studies of the University of Groningen. One possible output could be a data 'resource book' for footprint researchers. Since similar tools such as material flow analysis, life cycle analysis or environmental space use related data, such research can not only identify to what extent results for these other methods can be useful for footprint analysis, but also methods can be developed to interpret these results in terms of ecological footprints.

8. Find a more realistic and science-based percentage figure as a baseline for biodiversity preservation. In current footprint assessments, we account for biodiversity protection by simply deducting 12 percent from the existing biotically productive area, as suggested in the Brundtland report (WCED, 1987). Even though recommending the preservation of even 12 percent would be politically courageous, it is most likely insufficient. To make more realistic assessments, the conservation biology literature should be reviewed (and if necessary, research should be conducted) to identify a more realistic figure to use in footprint assessments.

9. Apply footprint assessment and human satisfaction measures simultaneously. A still unexplored dimension of footprint assessments is its link to human satisfaction or quality of life. Footprint assessments are not intended to advocate maximum reduction of human load. Neither do they indicate anything about people's quality of life. They only check whether people live within the means of nature. Therefore, footprint assessments need to be complemented by satisfaction measures to explore how to secure people's quality of life within the means of nature. After all, the prime focus for sustainability is promoting quality of life – based on the insight that living beyond ecological capacity endangers current and future quality of life.

Such research could identify in detail to what extent human satisfaction depends on resource throughput, and how society can be transformed from a resource intensive lifestyle to a way of life that depends on far less resource throughput while still maintaining a high quality of life. Fragments of the combined tool needed to do this analysis already exist. In a variety of fields such as medical research, political science and indicator research, there exists already a number of scales to measure people's satisfaction with their living situation. These scales will need to be adapted to become more relevant to sustainability questions. Also, to make them more robust, they have to be tested in a variety of contexts. The more they are tested, the more significant will be the results. Also, footprint scales at the household level need to become more sensitive to a variety of lifestyle choices and technological options in order to capture differences more accurately. But even in some first studies, the results will be sufficient for crude relative comparisons of populations and first indications about the correlation between quality of life and ecological footprint size. Such insights are crucial for better understanding how people can be motivated to reduce their footprint and to identify to what extent quality of life can be dematerialized.

Conclusions

Many crucial questions pertinent to building a sustainable society can be addressed by footprint research. These include measuring the capacity and the use of natural capital at the global, national and regional level, identifying the level of ecological overshoot, and tracking progress toward ecological sustainability. In addition, one could estimate to what extent human activities have been dematerialized, interpret existing data from an ecological perspective, and provide an overview aggregation (consistent with ecological principles and thermodynamic laws) of a variety of human impacts on the biosphere showing how they compete for ecological space. With the proposed research initiatives, the listed sustainability questions can be analyzed with more rigor and depth. By focusing on these issues and strengthening the analytical capacity and completeness of the ecological footprint method, it moves from being merely a pedagogical tool to become a strategic tool for policy analysis. This will help to strengthen the planning for sustainable businesses, communities and nations.

Fortunately, much of the proposed research can be done by using and recombining secondary data. Most primary data (particularly on the social science side) could be obtained through simple analytical tools (such as questionnaires). Obviously, the resolution and level of detail of the studies can vary depending on the resources and time available and depending on the potential application of the research results. Still, all of these applications can bring more light to one of the most challenging public policy questions humanity is facing: how to secure everybody's quality of life within the means of nature.

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Notes

1. This socio-ecological problematique represents the essence of most sustainability definitions. For example, the World Conservation Union (IUCN), together with the United Nations Environment Programme (UNEP) and the World Wide Fund for Nature (WWF) defined sustainable development in their 1991 report *Caring for the Earth: A Strategy for Living Sustainably* as 'improving the quality of human life while living within the carrying capacity of supporting ecosystems' (page 10). Also, the Union of Concerned Scientists write in their *Action for Global Sustainability* brochure that 'humanity must learn to live within the limits of natural systems while ensuring an adequate living standard for all people'. Similarly, Jonathan Lash, Director of the World Resources Institute, states that 'sustainable development is a concept that unites human aspirations for a better quality of life, for guaranteeing that there is food, housing, education, and adequate primary health care. There is a need to provide these things without destroying the Earth' (*Life, Wisdom, and Future* 1995, The Earth Council, San José, Costa Rica).
2. Projects include Alan Kelly, Alexander and Marlyn Mehlmann, and Mathis Wackernagel's footprint assessment of Eco-Teams for the Global Action Plan Sweden as well as the recent footprint questionnaire at Redefining Progress with Ritik Dholakia and Diana Deumling (visit www.rprogress.org).
3. Some of the intellectual predecessors are Georg Borgström who introduced the concept of imported ghost acres (Borgström, 1973), William Catton who discussed the implication of carrying capacity overshoot and imported phantom capacity (Catton, 1980), G. Higgins and his collaborators who analyzed the bioproductive potential of a number of countries (Higgins et al., 1983) and Ragnar Overby who introduced the idea of carrying capacity demand (1985).
4. One of the most impressive large scale examples is the State of Kerala in the south of India with over 30 million inhabitants. In spite of an average income of approximately one dollar a day, people in Kerala enjoy a level of health (as measured by longevity, child mortality and literacy) similar to industrialized countries. In addition, it has also reached replacement fertility. Therefore, Kerala is among the model societies of today, having met both sustainability challenges: low consumption and zero population growth. A more recent analysis is provided by Alexander (2000).

5. In fact, in the early days of the ecological footprint research, that is what we called the concept. In other words, the term appropriated carrying capacity is synonymous to ecological footprint.
6. A US football field measures 50×100 yards or $5000 \times (0.9144)^2\ m^2 = 4181\ m^2$ per football field; $7.2\ ha = 7.2 \times 10^4\ m^2$; $7.2 \times 10^4\ m^2/4.181 \times 10^3\ m^2 = 17.8$ football fields.
7. Between 1995 and 2000, the existing bioproductive space per capita dropped by over 0.1–2.1 ha per capita, assuming no net loss of bioproductive area over that time period.
8. Most of our sources are from UNSTAT, FAO. For the bioproductivity of agriculture, we use the data also available through the database of the web site http://www.fao.org.
9. According to the World Tourism Organization, the tourism industry generates 10 percent of the world's revenue and provides every 9th job. Since tourism with its increasing long-distance travel and material-intensive infrastructure developments (e.g. airports, and hotels with their water and energy consumption) may be above average in resource intensity per dollar spent, it is quite likely that tourism occupies over 10 percent of the world's ecological footprint.
10. The method of footprinting sea space has considerably evolved since the first 'footprints of nations' comparison we released for the RIO+5 Forum in March 1997. The two major improvements of the sea space assessment consist of allocating sea space proportional to nations' Economic Exclusive Zones rather than proportional to nations' populations, and of adjusting the sea space area in terms of its protein productivity rather than counting sea hectare for hectare at par with all other ecological space on the land. As a consequence, these improvements considerably altered the ranking of nations.
11. An award-winning and widely distributed integrated curriculum for grades 6–8 built on the footprint is *EcoVoyageurs: Reducing Our Ecological Footprint*, developed in 1996 by the Company for Education Communications (COED) in Toronto, Canada. It consists of 15 lessons and a colorful poster summarizing the themes the footprint touches. The project was sponsored by Lever-Pond's, Toronto. Visit www.ecovoyageurs.com. For inquiries contact COED at coedcomm@globalserve.on.ca, by telephone 416-955-9526 or fax 416-955-0815.
12. Mario Giampietro, personal communication, 1999.
13. As absurd as this may seem, there is serious scientific discussion on such options. One extreme example is Ming and Henninger's scientific paper collection on *Lunar Base Agriculture* (1989), where they write in the foreword: 'Whether or not plants will be grown on the Moon has not been answered; however, it is a possible scenario that will continue to be discussed by the planetary community. Consequently, this book will be a major source of information for many years to those seeking ways to produce food in space, particularly if the moon serves as an outpost to launch human exploration to our inner solar system.' They seriously study aspects such as 'Nutrient Availability and Element Toxicity in Lunar-Derived Soils' or 'Controlled Environment Crop Production: Hydroponic vs. Lunar Regolith'.

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