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Establishing national natural capital accounts based on detailed Ecological Footprint and biological capacity assessments

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Abstract

The protection of natural capital, including its ability to renew or regenerate itself, represents a core aspect of sustainability. Hence, reliable measures of the supply of, and human demand on, natural capital are indispensable for tracking progress, setting targets and driving policies for sustainability. This paper presents the latest iteration of such a measure: the Ecological Footprint. After explaining the assumptions and choice of data sources on which the accounts are built, this paper presents how the newest version of these accounts has become more consistent, reliable and detailed by using more comprehensive data sources, calculating and comparing yields more consistently, distinguishing more sharply between primary and secondary production, and using procedures to identify and eliminate potential errors. As a result, this method can now provide more meaningful comparisons among nations' final consumption, or their economic production, and help to analyze the Ecological Footprint embodied in trade. With the higher level of detail, the accounts can generate sectoral assessments of an economy or, as shown in a complementary paper in this series, time trends of all these aspects.

Keywords: Ecological Footprint; Method; Ecological deficit; Overshoot; Natural capital; Biophysical accounts

Purpose of this paper

This paper presents the latest iteration of an accounting tool to track a nation's demand on, and supply of, natural capital: the Ecological Footprint. Recognizing the central role of natural capital for sustainability, this paper explains the need for accounts that can comprehensively document human use of natural capital, and how the Ecological Footprint can fill this niche. It also points out the ability of such accounts to distinguish between the liquidation of natural capital and income from natural capital.

After providing the conceptual background and identifying the research question underlying the Ecological Footprint accounts, the paper explains recent advances in making the national accounts more consistent, reliable and detailed, and contrasts them to older and different Footprint methods. This includes the identification of the accounts' primary data sources and the clarification of the assumptions and choice of data sources on which the accounts are built. Two complementary papers (Wackernagel et al., 2004a, b) show applications of these national accounts, and discuss how they can be used for comparisons over time, what gaps still exist, and what kinds of improvements can be expected in future accounting methodologies.

Natural capital accounting

Natural capital and weak sustainability

The benchmark of a sustainable society has been variously defined along 'strong' and 'weak' criteria. While both aim at securing the best possible future well-being for people, strong sustainability builds on the assumption that natural capital is irreplaceable and therefore essential. At a minimum, strong sustainability

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stands for maintaining natural capital, independent of the development of human-made forms of capital. Weak sustainability assumes that human well-being is better served if the value of all combined assets is preserved, rather than giving special attention to maintaining natural capital, since technology may be able to substitute for lost ecological services (Pearce et al., 1989).

Whether a society pursues weak or strong sustainability, both paths need metrics to keep track of the various forms of capital. Market prices or other monetary valuation methods are unreliable means for informing about the long-term viability of ecosystems that provide goods and services such as topsoil creation, climatic stability, biodiversity, fuel, and fodder. Biophysical measures of natural capital are necessary, given that these uncertainties compromise our ability to manage social-ecological systems (Rees and Wackernagel, 1999).

Most broadly, natural capital contains all material aspects of this planet people find useful, minus the value people add to these materials. One way to make this concept more operational is to narrow natural capital down to its critical elements, hence 'critical natural capital' (Ekins et al., 2003). Assessments of the importance of and threats to natural capital can help identify those critical elements (De Groot et al., 2003). Perhaps the most important and thus most critical aspect of natural capital is the Earth's ability to provide conditions conducive for life. Conditions to make carbon-based life possible depend on a wide range of parameters such as level of solar power, limited temperature ranges and climate stability, access to certain chemical elements, and absence of others with noxious qualities, sufficient and continuous access to freshwater, to name just a few. These life-supporting qualities of natural capital are indispensable for maintaining life on this planet. In other words, they are more critical than other components of natural capital such as minerals deeply embedded in the Earth crust and used for industrial purposes. We call this part of natural capital that is essential for life the 'life-supporting natural capital'. It is this natural capital that provides the basic life-support services such as the ability to renew biomass-based resources and to assimilate waste, which we call the regenerative capacity of the biosphere.

If the goal is to secure living conditions on this planet, reliable tools are needed to document to what extent human activities compromise the biosphere's ability to regenerate. Measures for tracking the overall supply of, and human demand on, life-supporting natural capital are tools not only for documenting capacity and overuse of this capital. They are also useful for policy makers who wish to set targets for sustainability policies or test the ecological implications of policy choices.

What Ecological Footprint accounts measure

The accounts presented in this paper focus on those human activities that either depend on life-supporting services of natural capital or that compromise natural capital's ability to provide these services. Since both renewal and absorption depend on the health and integrity of ecosystems, regenerative capacity is a reliable proxy for the life-supporting capacity of natural capital. To track human demand on these services, we have developed accounts that measure how much of the biosphere's regenerative capacity is used by the human economy. These Ecological Footprint accounts document how much of the annual regenerative capacity of the biosphere, expressed in mutually exclusive hectares of biologically productive land or sea area, is required to renew the resource throughput of a defined population in a given year—with the prevailing technology and resource management of that year.

This specific research question drives the accounts, which aim to provide transparent, robust and comprehensive results with enough resolution to identify the trends and significance of various human activities. The ability to answer this question also sheds light on how much regenerative capacity exists within a given area compared with the regenerative capacity demanded by the population of that area, and how this has changed over time. Further, it allows researchers to identify what portion of the demand is supplied domestically versus the portion obtained through imports. It also provides a framework to compare the resources embodied in trade flows, compare the resource demand for supplying economic production versus feeding final consumption, and map to what extent regions are net debtors or creditors of ecological capacity (Sturm et al., 2000). Each of these inquiries can be conducted for each natural capital component captured in the accounts.

Using area as a measure of life-supporting natural capital reflects the fact that many basic ecosystem services are driven by surfaces where photosynthesis takes place. By focusing the measure on biologically productive areas that provide particular functions to people, rather than on the total amount of photosynthesis generated, the measure becomes sensitive to the quality of the biomass generation and its usefulness for the human economy.

By making the accounts work for any human population, they are scalable from the individual to the global level. This paper focuses on national Ecological Footprint accounts that provide detailed documentation of a national economy's aggregate demand on nature's services, allowing researchers to investigate the dependence of a country on ecological services, the competition between people's various uses of nature, and the distribution of resource use and capacity across the planet. Since these static accounts present yearly snapshots of ecological demand and supply, they capture the annual change in technologies in resource use, production efficiency and ecosystem management.

Complete national Ecological Footprint accounts measure the biologically productive space occupied exclusively to provide *all* of the resources a nation's population consumes and to absorb *all* of the wastes it generates, using prevailing technology and resource management. The presented accounts are the most complete and detailed ones yet produced. Recent leaps in the availability of national data have prompted the development of more reliable accounts with data resolution an order of magnitude greater than former accounts (Wackernagel et al., 1999). They, nevertheless, exclude ecological demands for which no reliable data sources exist, and consequently underestimate the full demand on nature.

The following section documents the methodology of these national Ecological Footprint accounts, while the subsequent section provides more detailed information on the data sources and calculation components.

Accounting method

Ecological Footprinting techniques: compound and component-based methods

Two distinct approaches exist for calculating Ecological Footprints: *component-based* and *compound* footprinting (Simmons et al., 2000). The component-based approach sums the Ecological Footprint of all relevant components of a population's resource consumption and waste production. This is done by, first, identifying all the individual items, and amounts thereof, that a given population consumes, and second, assessing the Ecological Footprint of each component using life-cycle data. The overall accuracy of the final result depends on the completeness of the component list as well as on the reliability of the life-cycle assessment (LCA) of each identified component. This approach produces erratic results, given LCAs' boundary problems, lack of accurate and complete information about products' life-cycles, problems of double-counting in the case of complex chains of production with many primary products and by-products, and the large amount of detailed knowledge necessary for each analyzed process. In addition, there may be significant differences in the resource requirements of similar products, depending on how they are being produced. Still, the process of detecting all components and analyzing their respective resource demands has heuristic value, judging from the hundreds of student projects replicating this approach worldwide.

Calibration with the compound method can overcome the weaknesses of the component method. Compound footprinting, which underlies the accounts presented in this paper, calculates the Ecological Footprint using aggregate national data. Such aggregate data captures the resource demand without having to know every single end use, and is therefore more complete than data used in the component approach. For instance, to calculate the paper Footprint of a country, information about the total amount consumed is typically available and sufficient for the task. In contrast to the component method, there is no need to know which portions of the overall paper consumption were used for which purposes, aspects that are poorly documented in statistical data collections.

Numerous studies have based organizational, municipal and regional assessments on national Ecological Footprints by calibrating component-based estimates on past and present compound national assessments presented here (Barrett et al., 2002; Best Foot Forward, 2002). This paper discusses the method's most recent compound accounts, while the complementary papers (Wackernagel et al., 2004a, b) show applications and discuss limitations and potential for improvement.

National Ecological Footprint accounts

In order to provide a quantitative answer to the research question of how much regenerative capacity is required to maintain a given resource flow, Ecological Footprint accounts use a methodology grounded on six assumptions:

1. *It is possible to track the annual amounts of resources consumed and wastes generated by countries.* These annual amounts can be measured in physical terms such as tonnes, joules or cubic meters. Consumption can be calculated by balancing domestic production for trade. Most countries have extensive annual statistics documenting their resource use, particularly in the areas of energy, forest products and agricultural products. United Nations agencies, like the Food and Agriculture Organization (FAO), compile many of these national statistics in a consistent format. Annual aggregation of consumption and production data make them compatible with most other national statistics that are updated on a yearly basis and accommodate seasonal variations between countries.

2. *The majority of these resource flows can be related to the bioproductive area necessary for their regeneration and the assimilation of their waste.* Bioproductive processes are associated with surfaces that can catch the sunlight for photosynthesis. Even three-dimensional processes that represent layers of such surfaces, as in aquatic ecosystems or rainforests, can be mapped on the two-dimensional area represented by the 'ideal spherical surface of the planet'. (Resource and waste flows that

cannot be measured in these terms are excluded from the assessment.)

3. *By weighting each area in proportion to its usable biomass productivity (that is, its potential annual production of usable biomass), the different areas can be expressed in terms of a standardized average productive hectare*. These standardized hectares, called 'global hectares' (gha), represent hectares with the potential to produce usable biomass equal to the world's potential average of that year. Usable refers to the portion of biomass that can be renewably harvested and is valuable to people, reflecting the anthropocentric perspective of the Ecological Footprint accounts. This standardization is applied both to people's ecological demand (Ecological Footprint) as well as to the supply of biological capacity (Biocapacity).

4. *The overall demand can be aggregated by adding all mutually exclusive resource-providing and waste-assimilating areas*. This means that none of the services or resource flows included in the Ecological Footprint accounts are provided on the same piece of land or sea space, ensuring that all areas are added only once to the Ecological Footprint. Otherwise, double-counting would inflate the estimation of overall demand. Contrary to some misinterpretations of the Ecological Footprint, this does not imply that areas are unable to provide a number of services simultaneously, or that the accounts are built on such an assumption. Ecological Footprint accounts merely document to what extent one human use of nature excludes other human uses of nature. The activities and resource uses captured in the accounts are called 'primary functions'. If an area provides timber but also, as a secondary function, collects water for agricultural irrigation, the Ecological Footprint only includes timber use, the primary function. In cases of double cropping, both crops are included, but only at their percentage share of the crop area. For instance, if 1 ha produces a rotation of beans and corn in a given year, the sum of the beans Footprint plus the corn Footprints would be 1 ha. The allocation of this 1 ha between beans and corn can be assigned proportional to the productivity they are each locking up, or if this information is not available proportional to the respective biomass.

5. *Aggregate human demand (Ecological Footprint) and nature's supply (Biocapacity) can be directly compared to each other.* Both use standardized hectares to measure aspects of natural capital—the demand on natural capital versus the ability of natural capital to meet the demand. Hence, the component and aggregate areas are commensurable.

6. *Area demand can exceed area supply.* A Footprint greater than the Biocapacity indicates that demands exceed the regenerative capacity of existing natural capital. For example, the products from a forest harvested at twice its regeneration rate have a Footprint twice the size of the forest. We call the amount of overuse ecological deficit. Ecological deficits are compensated in two ways: either the deficit is balanced through imports (ecological trade deficit); or, as in this forest product example, the deficit is met through overuse of domestic resources, leading to natural capital depletion (ecological overshoot).

The national Ecological Footprint accounts use economic and biophysical data published primarily by international statistical and scientific agencies. Data gaps in these statistics are filled with research from governmental, non-profit, academic, and private sector sources.

Complete national Ecological Footprint accounts depend on comprehensive and reliable data sources available on a global scale. By basing current accounts primarily on official data sources, they document what the ecological implications are if these data were correct. As a consequence, like other measures that draw on data from official statistics without information about the margin of error of the underlying data, the margin of error of national Ecological Footprint accounts cannot be quantified. The section 'Reliability and validity of Ecological Footprint accounts' summarizes, in qualitative terms, errors that affect the accuracy of the results. There is value in interpreting official data since they synthesize this information, and give governments the opportunity to get more accurate results as they make better data available. Future research will contrast these accounts with accounts built on independent data, resulting in more transparency and the possibility to analyze the accuracy of the data.

The impetus for the comprehensive revisions of the Ecological Footprint accounts presented in this paper was the release of the 'Food Balance Sheets' by *FAOSTAT*, an online, electronic database of international statistics published by the UN Food and Agriculture Organization. This standardized database documenting production, import and export data in a common accounting framework replaced manual data entry from disparate printed materials used in previous accounts, greatly increasing the reliability of input and expanding the number of data points of the calculations. Also, they enabled more reliable Ecological Footprint analysis from the perspectives of trade and production, in addition to consumption, particularly since some of the new data sources also distinguish changes in stocks, production, waste and secondary uses.

Additional databases made possible methodological improvements in forests, fisheries, energy, and land productivity. They include the *Forest Resource Assessment 2000* (FAO, 2000a), the *Temperate and Boreal Forest Resource Assessment 2000* (FAO and UNECE, 2000), *FISHSTAT* (FAO, 2000b), the *Statistical Review of World Energy 2001* (British Petroleum, 2001), *Livestock Environment Interactions* (Steinfeld and de Haan, 1997), *Global Fibre Supply Model* (FAO, 1998), and *Global Agro-Ecological Zones 2000* (IIASA and FAO, 2000).

Thanks to more comprehensive and detailed data sets, this revision of the accounts allowed the data to be compiled in a more consistent and coherent framework.

The account components

The accounts are divided into two parts: the ecological supply (or bioproductive areas) and the demand on nature (or Ecological Footprints). This section explains the components of both. These components include the definition of bioproductive areas and their conversion from unweighted hectares to standardized global hectares through the use of equivalence and yield factors (Fig. 1).

Bioproductive areas

Globally, we identify 11.4 billion ha of distinct bioproductive areas—cropland, forest, pasture, fisheries, and built-up land—that provide economically useful concentrations of renewable resources. These 11.4 billion ha cover a little under one quarter of the planet and include 2.3 billion ha of marine and inland fisheries and 9.1 billion ha of land. The land area comprises 1.5 billion ha of cropland, 3.5 billion ha of grazing land, 3.8 billion ha of forest, and an additional 0.3 billion ha of built-up land assumed to occupy potential cropland (Eurostat, 2000; FAO, 1999; SEI, 1998; WRI, 2000). These areas concentrate the bulk of the biosphere's regenerative capacity. We have not yet been able to estimate how much of the total usable annual biomass generation (Net Biosphere Production or NBP) is concentrated on these 11.4 billion ha, but would be surprised if it were less than 85%. While the remaining areas of the planet are also biologically active, such as the deep oceans or deserts, their renewable resources are not concentrated enough to be a significant addition to the overall Biocapacity.

The common unit: global hectare

Ecological Footprint accounts express the use of built-up areas, and the consumption of energy and renewable resources—crops, animal products, timber, and fish—in standardized units of biologically productive area, termed global hectares. Each global hectare represents an equal amount of biological productivity.

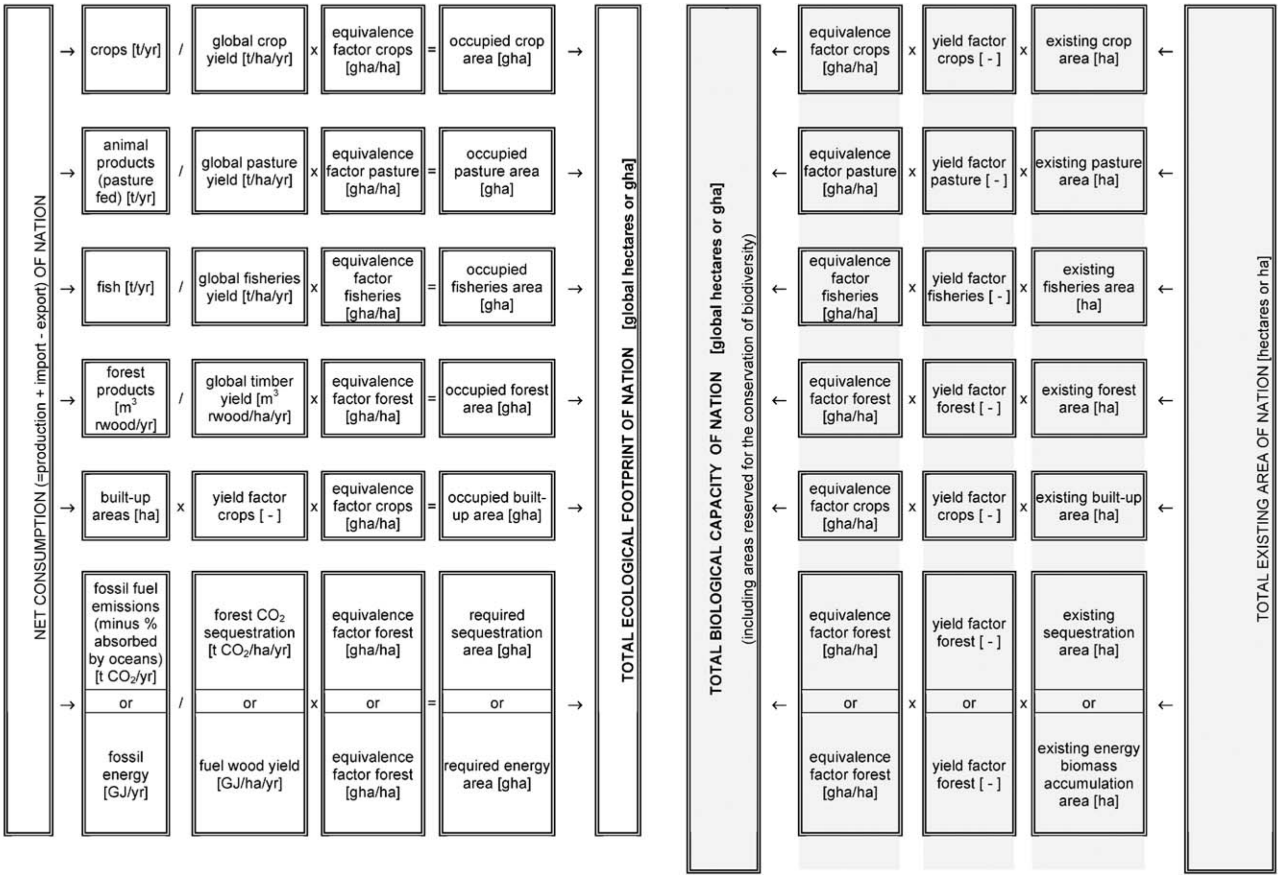

Fig. 1. Structure of Footprint and Biocapacity calculations. This scheme summarizes how the Ecological Footprint translates net consumption and bioproductive areas into areas of global average productivity. For simplification, this scheme excludes secondary products and nuclear power.

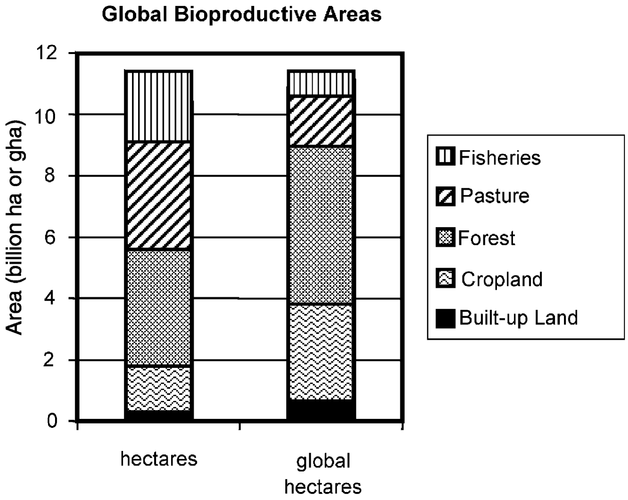

Fig. 2. Globally, the number of unadjusted hectares and the number of global hectares of bioproductive space are identical. The hectares for each type of bioproductive area are converted into global hectares by weighting their productivity against the world average productivity. This conversion is calculated using equivalence factors (capturing the productivity difference among land-use categories) and yield factors (capturing the difference between local and global average productivity within a given land-use category). *Source*: Loh (2002).

One global hectare is equal to 1 ha with productivity equal to the average productivity of the 11.4 billion bioproductive ha. Here, productivity does not refer to a rate of biomass production, such as net primary production (NPP). Rather, productivity is the potential to achieve maximum agricultural production at a specific level of inputs (see the next section). Thus, 1 ha of highly productive land is equal to more global hectares than 1 ha of less-productive land. Global hectares are normalized so that the number of actual hectares of bioproductive land and sea on this planet is equal to the number of global hectares on this planet (see Fig. 2). Global hectares allow for the meaningful comparison of the Ecological Footprints and the Biocapacities of different countries, which use and have different qualities and mixes of cropland, grazing land, and forest. Two conversion factors—equivalence factors (constant for all countries for a given year) and yield factors (specific for each country and each year)—translate each of the biologically productive areas from hectares into global hectares.

Equivalence factors

Equivalence factors represent the world average potential productivity of a given bioproductive area relative to the world average potential productivity of all bioproductive areas. Specifically, an equivalence factor is the quantity of global hectares contained within an average hectare of cropland, built-up land, forest, pasture, or fishery.

The equivalence factors for cropland, forest, pasture, and built-up area are derived from the suitability index of *Global Agro-Ecological Zones (GAEZ) 2000*, a spatial model of potential agricultural yields (IIASA and FAO, 2000). *GAEZ* maps the suitability of agricultural production by optimizing crop varieties with data on soil type, growing season, slope, temperature, and precipitation. Ecological Footprint accounts value fisheries according to their capacity to supply animal protein relative to that of pasture. The equivalence factors for 1999 are listed in Table 1.

The equivalence factor describes the potential crop yields attainable in an area at an explicit level of inputs, regardless of current management practices or rates of biomass production (IIASA and FAO, 2000). As used here, potential productivity differs from measures of ecosystem productivity, such as NPP, in that it describes the inherent ability to support agricultural production, and therefore human populations. Building the accounts on potentially usable productivity has a number of advantages. Focusing on ‘usable’ productivity allows us to contrast amounts of consumption and production in more precise terms. For instance, the amount of roundwood harvested as well as the amount of roundwood available for harvest can be measured far more accurately than removed or compromised NPP, which would need to encompass all biomass, including undergrowth, bark, leaves and sub-soil plant parts. Using the

Table 1
Equivalence factors (1999)

Bioproductive area	Global hectares/ha
Cropland (overall)	2.1
Primary	2.2
Marginal	1.8
Pasture	0.5
Forest	1.4
Fisheries	0.4
Built-up area	2.2[a]
Hydropower area	1.0
Fossil Fuels (Forest)	1.4

Source: Loh (2002).

[a] Note that built-up area is assumed to be located mostly on prime agricultural land. Hence, built-up area has the same equivalence factor

Table 2
Peruvian yield factors (1999)

Bioproductive area	(—)
Cropland (overall)	n.a.
Primary	0.9
Marginal	1.2
Pasture	1.1
Forest	1.1
Fisheries	3.4
Built-up area	0.9

Source: Loh (2002).

land's 'potential' productivity at a specified level of technical inputs makes equivalence factors more robust over time, whereas equivalence factors based on actual productivity shift markedly with the intensiveness of agriculture, making the interpretation of time series difficult.

Yield factors

Yield factors (Table 2) describe the extent to which a biologically productive area in a given country is more (or less) productive than the global average of the same bioproductive area (e.g. the Swiss yield factor for crop land would be the ratio between Swiss and world average cropland yields). Each country has its own set of yield factors, one for each type of bioproductive area. Each year the yield factor is calculated anew. Specifically, the yield factor is the ratio between the area a country uses in the production of all goods in a given category—i.e., timber from forests, forage from pastures, etc.—calculated with national yields, and the area that would be required to produce the same goods with world average yields. The yield factor reflects prevailing technology and management practices, in addition to the inherent renewable resource productivity of a country. For each country, the yield factor reflects the national average, which can vary dramatically, particularly in countries stretching over a vast number of climate zones such as Canada or Chile. For local analyses with a higher resolution, yield factors would have to be calculated for each locale.

Calculation of the Footprint

Cropland, pasture, forest, fisheries, and built-up areas provide for mutually exclusive demands on the biosphere, the sum of which equals the total Ecological Footprint. Each of these categories represents an area in hectares, which is then multiplied by its equivalence factor to obtain the Footprint in global hectares (Fig. 1):

$$\text{Footprint (gha)} = \text{Area (ha)} * \text{Equivalence Factor (gha/ha)}.$$

Consumption, production, and trade

National accounts distinguish products produced within a country from products consumed by a country. Production includes all domestically produced goods, regardless of their final destination. The final Footprint, however, documents consumption, which is calculated by adding imports to, and subtracting exports from, domestic production (net consumption = domestic production + imports−exports).

If country A exports 1 ton of mutton to country B, the Footprint of feed, pasture, and energy required to produce this ton of mutton is deducted from country A and added to country B to determine the Footprint of consumption. Despite these adjustments for trade, some consumption activities such as tourism and international air travel are attributed to the country where they occur, or where planes are fueled, rather than to the travelers' countries of origin. This distorts the relative size of some countries' footprints, but does not affect the global result.

Footprint of renewable resources

Cropland, pasture, forests, and fisheries encompass global ecosystems that supply the human economy with the bulk of its biologically renewable resources. The Footprint calculation for each of these areas is the sum of the Footprints of all products consumed within that category. The Footprint of cropland, for example, includes cereals for human consumption, cotton, processed oils, and fodder crops for livestock.

Primary products. These products describe the unprocessed output of a given area, which may be used directly with minimal alteration or be processed into a secondary product. In the case of cropland, pasture, and forest this includes the immediate products of photosynthesis, such as raw fruits and vegetables, forage for livestock, or unprocessed roundwood. For fisheries, the primary products are unprocessed fish harvested from marine and inland fisheries. The Footprint of these products represents the biological and technical capacity required for their production, standardized using the average global yield:

$$\text{Area (ha)} = \frac{[\text{Production} + \text{Imports} - \text{Exports (tons)}]}{\text{Global yield (tons/ha)}}.$$

Secondary products. These products are goods derived from primary products, including meat and milk, paper, and farmed fish. Table 3 provides a few examples of primary and secondary products. While the Ecological Footprint of a primary product is calculated from the global yield, the Footprint of a secondary product equals the Footprint of its parent primary product. In other words, the part of the Ecological Footprint of a primary product that is used for manufacturing a

Table 3
Examples of primary and secondary products

Component	Primary	Secondary
Cropland	Maize	Maize germ oil
	Sunflower seed	Sunflower seed oil
	Alfalfa	Alfalfa raised beef
Pasture	Forage	Milk
Forest	Roundwood	Sawnwood
	Fuelwood	none
Fisheries	Demersal fish	Fish liver oil
	Pelagic fish	Salmon from aquaculture

secondary product (e.g., cereals for pork meat or roundwood for paper) is shifted to the secondary (or daughter) product. While a primary product will have an identical Footprint regardless of its origin, the Footprint of a secondary product changes according to the conversion efficiency of a country. The Footprint of a secondary product is only added to the total Footprint of consumption when traded; the Footprint of a secondary good that is produced but not traded is included in the processing Footprint of its parent product.

Note that the Ecological Footprint accounts only include the area demand of these primary and secondary products, not other potential effects on future loss of bioproductivity. If future bioproductivity will indeed decline, this will affect Biocapacity estimates of future years. Ideally, Footprint estimates should also include the area demand of agricultural side effects such as water pollution from intensive animal farming, but in current accounts these aspects are missing for lack of data. This is another reason why our demand on nature estimates under-represent the real demand.

Imports of secondary products use the global conversion factor, and domestically produced secondary products use the national conversion factor. The area of exports is weighted in proportion to the amount of products imported and produced domestically and their respective conversion factors:

$$\text{Area of Imports}_{\text{secondary}}\ (\text{ha}) = \text{Imports}_{\text{secondary}}\ (\text{tons}) * \frac{\text{Global Conversion Efficiency}\ (\text{tons}_{\text{primary}}/\text{tons}_{\text{secondary}})}{\text{Global yield}_{\text{primary}}\ (\text{tons/ha})},$$

$$\text{Area of Production}_{\text{secondary}}\ (\text{ha}) = \text{Production}_{\text{secondary}}\ (\text{tons}) * \frac{\text{National Conversion Efficiency}\ (\text{tons}_{\text{primary}}/\text{tons}_{\text{secondary}})}{\text{Global yield}_{\text{primary}}\ (\text{tons/ha})},$$

$$\begin{aligned}\text{Area of Exports}_{\text{secondary}}\ (\text{ha}) &= \text{Exports}_{\text{secondary}}\ (\text{tons})\\ &\quad *[(\text{Areas of Imports}_{\text{secondary}}\ (\text{ha})\\ &\quad\quad + \text{Area of Production}_{\text{secondary}}\ (\text{ha}))/\\ &\quad (\text{Imports}_{\text{secondary}}\ (\text{tons}) + \text{Production}_{\text{secondary}}\ (\text{tons}))].\end{aligned}$$

Footprint of built-up area and hydropower

The Ecological Footprint assumes that human settlement and infrastructure most often occupy agriculturally fertile regions. Some of the settlement area is paved over; other areas are still bioproductive such as gardens or parks. The Footprint includes those areas in terms of their foregone agricultural productivity. Hence, built-up area equals the same amount of cropland it replaces, adjusted for its productivity using the yield factor of cropland:

$$\begin{aligned}\text{Footprint}_{\text{built-up}}\ (\text{gha}) &= \text{Area}_{\text{built-up}}\ (\text{ha})\\ &\quad *\text{Equivalence Factor}_{\text{built-up}}\ (\text{gha/ha})\\ &\quad *\text{Yield Factor cropland}\ (\text{—}).\end{aligned}$$

Due to a high variation in the productivity of land inundated by hydropower reservoirs and the lack of data documenting their distribution, this area receives a world average equivalence factor of 1.0 (and a yield factor of 1.0). Since hydroelectricity consumption is better documented than reservoir area, a constant conversion factor converts energy use into area:

$$\begin{aligned}&\text{Footprint}_{\text{hydro area}}\ (\text{gha})\\ &\quad = \text{Energy}\ (\text{GJ}) * \text{constant}\ (\text{GJ/ha})\\ &\quad\quad *\text{Equivalence Factor}_{\text{hydro area}}\ (\text{gha/ha}).\end{aligned}$$

Footprint of fossil fuels and nuclear energy

While the Footprints of crops, forest products, animal products and fish are calculated in a straightforward way, the Footprint of fossil fuels and nuclear energy can be estimated from a number of different perspectives. The research question 'how much regenerative capacity is required to maintain the throughput of fossil fuel through the human economy?' can be addressed, for instance, from a maintenance of natural capital perspective or a waste perspective. The latter addresses the additional capacity the biosphere would need to either accommodate the waste, assuming that the supply of fossil fuel is far less limiting than the biosphere's ability to cope with the waste. We refer to this latter approach as the area required for waste assimilation. In contrast, the former approach examines the capacity needed to replace the consumed energy by supplying a biomass substitute. This is how the two methods work.

Waste assimilation. The CO_2 sequestration Footprint estimates the additional biologically productive area needed to sequester atmospheric CO_2 emissions through afforestation. The sequestration area is calculated by deducting the approximately one-third of anthropogenic emissions absorbed by the oceans from the total anthropogenic emissions (IPCC, 2001).

$$\text{Area (ha)} = CO_2\ \text{Emissions (tons)} * \frac{(1 - \text{fraction absorbed by ocean})}{\text{Sequestration Rate}}\ (\text{tons/ha}).$$

This approach does not suggest that CO_2 sequestration is the solution to climate change. Rather, it illustrates how much larger the world would need to be in order to cope with anthropogenic CO_2. In doing so, it demonstrates the necessity of CO_2 reduction schemes, since the potential for the sequestration is limited in space (amount of area available for afforestation) and time (planted forests are net sinks for the few decades before they mature and lose their absorptive capacity). CO_2 emission data can be obtained from various sources, including CDIAC (1999) and IEA (2001).

Biomass substitution. The biomass substitution approach calculates the area needed to replace fossil fuels with their energy equivalent in fuelwood. Fuelwood is chosen as the default replacement as it has been the historically dominant fuel for most societies and the primary fuel the biosphere supplies without human modification. Alternative biofuels with lower space requirements (such as ethanol fuel) are possible but do not occur without active human intervention and industrial processes. Obviously, if higher yield alternatives were used, they would replace fuelwood and reduce the Footprint accordingly. The rate of fuelwood production equals the growth rate of roundwood multiplied by an expansion factor to account for additional biomass used for fuel (limbs, small trees, etc.):

$$\text{Area(ha)} = \text{Energy (GJ)}/[\text{Roundwood yield (GJ/ha)} \\ *\text{Expansion Factor (—)}].$$

If forests are managed for fuelwood, higher yields can be achieved which would also reduce the Footprint.

Nuclear energy. The prevalence of nuclear power in some nations draws attention to its role in international metrics of demand on natural capital. The nuclear component differs from the other parts of the Footprint in that it produces wastes for which the biosphere has minimal assimilative capacity. While they are not designed to release their waste, the fact is that some have (Chernobyl), and that the problem of the long-term waste storage remains unsolved. One could argue that similar to PCBs, nuclear power should not be included in Footprint accounts to keep them logically consistent since the use of these substances should be phased out if humanity does not want to run the risk of increasing the concentration of these substances in the biosphere. But this omission could also be (mis)interpreted as a higher ecological performance of countries with nuclear power. We chose for our current Ecological Footprint accounts to include nuclear power as if it were fossil fuel. Accepting the economic necessity and ecological precaution leading to the eventual replacement of nuclear power with a sustainable alternative, the current energy infrastructure makes fossil fuels their most likely replacement. (The accounts provide users with the option to exclude the nuclear Footprint from the results.) Other methods are conceivable too: it may be possible to quantify the area put at risk by accidental release into the environment by basing estimates on historical precedent. Or, it could be argued that the Ecological Footprint documents the actual bioproductive area occupied at a given point in time, and that the Footprint of a nuclear accident should be incorporated when it occurs, eliminating the need for a risk based assessment.

Embodied energy in trade. In order to determine the Footprint of consumption, national energy statistics must be adjusted for the energy embodied in traded goods. National energy production data are more readily available than either trade data or the embodied energy in traded goods. The Footprint of consumption adds imports and subtracts exports by converting quantities of agricultural and manufactured goods into their energy equivalents, using best available data on energy intensity of goods. In our current accounts, we use the same energy intensities for each country. These values are then assigned CO_2 equivalents according to the fuel mix that went into their production.

Calculation of Biocapacity

Biocapacity, or the supply side of the equation, is the counterpart of the Footprint, or the demand side. A nation's total Biocapacity is the sum of its bioproductive areas, also expressed in global hectares (Fig. 1). We transform each bioproductive area into global hectares by multiplying its area by the appropriate equivalence factor and the yield factor specific to that country:

$$\text{Biocapacity (gha)} = \text{Area (ha)} \\ *\text{Equivalence Factor (gha/ha)} \\ *\text{Yield Factor (—)}.$$

The Biocapacity captures the entire bioproductive area to which that nation has exclusive claim and represents the maximum theoretical rate of resource supply that can be sustained on its territory under prevailing technology and management schemes. This contains all bioproductive areas to which that country has exclusive claim, including regions that are not utilized for reasons of geography, economics, or conservation. Given adequate information, however, the Biocapacity of each bioproductive area may be divided into accessible and inaccessible sub-regions. Each sub-region may have separate yield factors, as the most productive areas are the most likely candidates for settlement and resource extraction. Recent data on the percentage of forests in inaccessible and protected areas already make sub-regional Biocapacity assessments possible (FAO, 2000a; FAO and UNECE, 2000). The Footprint can then be compared with its respective bioproductive area to isolate the concentration of resource extraction and consumption to a restricted area.

Assuming the mutual exclusivity of national Biocapacities and the claim of all bioproductive areas within national territories, the global Biocapacity equals the sum of all national Biocapacities. The global Biocapacity can also be expressed as follows:

$$\sum P_i E_i = A,$$

where P is the actual, physical hectares of bioproductive area, E is the equivalence factor for each area of type i, and A is global Biocapacity expressed in standardized hectares.

Ecological deficit and ecological overshoot

A comparison of the Footprint and Biocapacity reveals whether existing natural capital is sufficient to support consumption and production patterns. A country whose Footprint exceeds its Biocapacity runs what we term an ecological deficit, which is possible only by two means: imports of Biocapacity from other nations (ecological trade deficit) and the liquidation of natural capital (ecological overshoot). We define ecological deficit (from the perspective of consumption) as

$$\begin{aligned}&\text{Ecological deficit (gha)}\\&\quad = \text{Biocapacity (gha)} - \text{Footprint}_{\text{consumption}}\text{ (gha)}.\end{aligned}$$

If a country has an ecological remainder—i.e., holds more Biocapacity than Footprint, and therefore has no ecological deficit—this remainder may still be used for providing services that are consumed in other countries. If these services were sold to a second country, then the corresponding demand on the first country's Biocapacity would be part of this first country's production Footprint, as well as part of the second country's Ecological Footprint of consumption.

Countries with low per capita Biocapacities—typically resulting from high population densities (Bangladesh, the Netherlands) or inhospitable climates (Ethiopia, Saudi Arabia)—do not have the capacity to meet their resource demand, and import food and timber from countries with agricultural, fishery, or timber remainders, such as Canada or Brazil. Subtracting the Footprint of consumption from the Footprint of production yields the ecological trade deficit, or the net import of biological capacity.

$$\begin{aligned}&\text{Ecological trade deficit (gha)}\\&= \text{Footprint}_{\text{consumption}}\text{ (gha)} - \text{Footprint}_{\text{production}}\text{ (gha)}.\end{aligned}$$

Ecological deficits not balanced through trade are met through the overuse of domestic or, in the case of fossil fuels, global resources, resulting in overgrazed pastures, depleted fisheries, degraded forests, and the accumulation of carbon emissions in the global atmosphere. This phenomenon, termed ecological overshoot, is a state in which resources are used more rapidly than the biosphere can replenish them or assimilate their waste, breaching the principle of strong sustainability at the global level. Domestic ecological overshoot equals the Biocapacity minus the Footprint of production.

$$\begin{aligned}&\text{Ecological overshoot (gha)}\\&\quad = \text{Biocapacity (gha)} - \text{Footprint}_{\text{production}}\text{ (gha)}.\end{aligned}$$

It is possible, although unlikely, for a country to run a negative ecological trade deficit (remainder) while in a state of ecological overshoot. In such a situation, the country would literally be liquidating natural capital to service exports. A global ecological deficit always means ecological overshoot, since there is no other planet to import from. However, an absence of ecological deficits (at the global, national or local level) does not necessarily mean sustainable resource management since local overuse can still lead to local overshoot or other systematic overuse of natural capital.

It is crucial to note that the Biocapacity represents the theoretical maximum resource capacity for a given year. While ecological overshoot by definition reveals the degradation of natural capital, the ecological remainder does not guarantee the sustainability of production practices. Rather, as the Footprint of production approaches the Biocapacity and the ecological remainder narrows, the likelihood that the country will experience environmental stress or degradation escalates, at least over longer periods of time. In other words, a decreasing ecological remainder ratchets pressures on ecosystems, increasing the need to examine environmental maladies omitted by Ecological Footprint accounts, such as biodiversity loss or water pollution. This does not mean that biological conservation is hopeless in the face of high human pressures. Examples are subtropical, arid places such as karstic Mediterranean landscapes where high conservation values can be achieved in the presence of 'traditional' low input agriculture (Wrbka, personal communication). But with more pressure, conservation efforts become more difficult. An ecological overshoot equal to zero provides no margin of error and will only avoid resource degradation under perfect management schemes and absence of any other pressures not included in Ecological Footprint accounts.

Description of bioproductive areas and data sources

Cropland

The accounts include over 70 crops and 15 secondary products, and the quantity of each product allocated to feed, seed, food, waste, processing, and non-food uses. In addition to imports and exports, the cropland accounts record national stock changes.

The FAO estimates that cropland covers roughly 1.5 billion ha worldwide, of which approximately 1.3 billion ha are harvested. Unharvested cropland covers 0.2 billion ha and includes temporary pasture, failed or unreaped harvests, temporarily fallow land, and shoulders, shelterbelts, and other uncultivated patches (FAO, 1999).

Cultivated cropland comprises primary and marginal cropland, which receive separate equivalence factors to reflect different land qualities and crops. Marginal crops include sorghum, millet, olives, and fodder grasses, such as alfalfa and clover cultivated for silage. We introduced these categories recognizing that some crop areas have inherently lower productivities and the choice of agricultural technology does not explain the low yields. Without introducing a marginal crop area category, a hectare with average millet or average olive yield would be counted as equal to a hectare of average potato or average rapeseed yield. Note that the crops in this marginal category are not homogeneous either. Some uses such as intensive fodder cultivation may put significant pressure on local biodiversity, while olive trees may add ecological benefits to the area through shading, water and soil retention.

The accounts measure the area occupied by cropland to the exclusion of other land uses but do not document degradation from agricultural practices, such as long-term damage from topsoil erosion, salinization, aquifer depletion, and nitrogen runoff. The energy embodied in agricultural inputs—fertilizer, pesticide, mechanization—is captured in the Footprint.

Forest

Roundwood and fuelwood constitute the primary products of the forest Footprint. Fuelwood includes charcoal, and roundwood, rough lumber in its felled state, is subsequently processed into four commodities: sawn wood, wood-based panels, paper and paperboard, and wood pulp.

According to FAO (2000a), 3.8 billion ha of forest exist worldwide. The World Resources Institute and others have critiqued the report for overstating the health of global forests and underestimating deforestation rates. Hence we consider this data set to be an underestimate of forest pressures, leading to optimistic assessments of the forest sector in the presented national accounts. This report, as well as FAO and UNECE (2000) and IPCC (1997), provide information on plantation type, coverage, national timber yield, and areas of protected and economically inaccessible forest. Data on bark removal, timber removals of dead trees, and felled but unharvested trees consider country-specific logging practices.

Our mechanistic assessment of the forest ignores additional pressures on forests, such as soil impacts from planting exotic tree species, or sensitivity to pathogen outbreak or storm damage that could affect long-term productivity of forests. However, once these effects occur, they will reduce the measured Biocapacity of the forests.

Pasture

FAO (1999) estimates 3.5 billion ha of permanent pasture worldwide: 'land used permanently (five years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land)'. The pasture Footprint assesses the demand on this resource by estimating the percentage of livestock energy requirements derived from concentrate feeds, forage crops, and crop residues. The remaining energy requirements are attributed to pasture. National pasture productivities are estimated from tropical, temperate, and arid grassland primary production data published in IPCC (2001), the distribution of national pastures among these biomes, and national forage crop yields. These advancements permit an initial investigation into grazing pressures, but the reliability of the data sets and methodology require improvement, particularly in transition zones between high- and low-productive ecosystems such as the Sahel zone in sub-Saharan Africa. Data sets detailing the carrying capacity of global pastures would greatly facilitate these revisions, but are not available on a global level. The paucity of pasture data is at odds with its economic importance and relevance to food security. Until such data become available, estimates of grazing footprints will come from the metabolic requirements of livestock populations and pasture productivities.

One aspect of the methodology requiring further research is difficulty assessing forage supply and demand. Poor data are one obstacle; another is significant use of crop residues and other complementary crops not listed in the FAO statistics. These might include household scraps, garden by-products, or plants growing along paths, roads or unclaimed common areas.

Fisheries

The latest revision of the accounts have led to a more realistic representation of fisheries use by (a) reflecting the by-catch and trophic level of national fish catches, (b) using a more consistent premise behind the normalization of ocean productivity to land productivity, (c) accounting for widely divergent productivities and areas of the various continental shelves for the allocation of Biocapacities, and (d) including freshwater fisheries and aquaculture.

The accounts reference eight categories of fish and aquatic animals and one category of aquatic plants. These nine categories subsume an additional 42 species groups, each possessing an average by-catch, or discard rate, and trophic level used to calculate the demand on nature represented by the catch of one unit of each species.

Higher trophic level fish consume a far greater portion of the primary productivity of the oceans than lower trophic level fish—roughly 10 times per trophic level (Pauly and Christensen, 1995). Where earlier Footprint accounts calculated the fish Footprint solely in proportion to the tonnage of fish, they now calculate it as a function of tonnage and trophic level. Thus, a ton of cod at trophic level 4 has a Footprint 10 times greater than a ton of sardines at trophic level 3.

$$\begin{aligned}&\text{Yield (kg/ha)}\\&\quad = \text{Max. PPR (kg/ha)}*(\text{Transfer Efficiency}^{(1-\text{TL})})\\&\qquad *\text{Yield Factor (—)/Discard Rate (—)}.\end{aligned}$$

The maximum PPR, or primary production requirement, equals the maximum equivalent net primary production that can be harvested; TL equals the trophic level of the catch; and transfer efficiency represents the biomass transferred between trophic levels at a default transfer efficiency of 10% (Pauly and Christensen, 1995). While actual transfer efficiencies may deviate from this typical default value of 10%, this number does not affect the global Footprint but only the relative Footprint associated with given species. For instance, assuming a lower transfer efficiency would increase the fish Footprint of those nations who eat higher on the fish food-chain.

The majority of the marine fish catch occurs on the continental shelves. Excluding inaccessible or unproductive waters, these comprise 2.0 billion ha. Although a mere fraction of the ocean's 36.3 billion ha, these 2.0 billion ha provide over 95% of the marine fish catch (Pauly and Christensen, 1995; Sharp, 1988; WRI, 2000). Inland waters add another 0.3 billion ha, making for 2.3 billion ha of potential fisheries out of the 36.6 billion ha of ocean and inland water that exist on the planet (FAO, 1999). FAO fish catch figures are compared with FAO's sustainable yield figure of 93 million tons per year (FAO, 1997). The fish Footprint assumes an additional by-catch according to the species composition of national fish catches.

Earlier accounts based fishing areas on national Exclusive Economic Zones (EEZ). For lack of data, they assumed all areas equally productive. The productivity of national waters is now estimated by fish catch potential in 26 continental shelf zones (Sharp, 1988). Inland water and continental shelf areas have replaced the EEZ to obtain a far more accurate distribution of global fishing capacity. The diminished fishing area—from 3.1 billion to 2.3 billion ha—consequently reduces the global Footprint and Biocapacity, introducing the largest source of change into the accounts. The reduced Biocapacity, however, does not indicate a reduction in global productivity but only a concentration of the same productivity in a smaller region.

Infrastructure

Infrastructure for housing, transportation, industrial production, and capturing hydroelectricity occupies built-up land. This area is the least well documented, since low-resolution satellite images are not able to capture dispersed infrastructure and roads. Data from Eurostat (2000) and SEI (1998) suggest a global total of 0.3 billion ha of built-up land. The accounts assume that built-up land replaces arable land, as most human settlements are located in fertile areas. Hydroelectricity consumption data can be obtained from British Petroleum (2001).

Reliability and validity of Ecological Footprint account

As for any other scientific measurement tool, the results need to be scrutinized on their reliability and validity. This question is slightly more complex with accounts that aggregate a vast array of data, and data that are not delivered with error bars. Hence, considerable care is taken to minimize any data inaccuracies or calculation errors that might distort the Ecological Footprint accounts. Overall, we have constructed the accounts to err on the side of over-reporting Biocapacity and under-reporting Ecological Footprints. We believe that it is unlikely that any errors will significantly undermine the conservative bias of the accounts. We have identified and attempt to minimize six potential sources of error:

1. *Conceptual and methodological errors*. These include:
    (a) *systematic errors in assessing the overall demand on nature*. Some demands, such as freshwater consumption, soil erosion and toxic release are excluded or incompletely covered in the calculations. This typically leads to underestimates of ecological deficit.
    (b) *allocational errors*. Incomplete or inaccurate trade and tourism data may distort the distribution of the global Footprint among producing and consuming nations. This means, for example, that the consumption of a Swedish tourist in Mexico may be allocated to Mexico rather than Sweden. However, this does not affect the estimate of humanity's overall demand on nature.
2. *Structural and data entry errors in the calculation sheets*. Error-detecting algorithms, the modular architecture of the calculation sheets, automatic cross-checks or tests for outliers in data time series and other techniques are used to identify and correct

these potential errors. Minor errors are more difficult to detect but have minimal impact on the reliability of the accounts.

3. *Erroneous assumptions for estimating missing data.* Estimating data gaps is limited to only one quarter of one minor section of the accounts: the embodied energy in trade. National estimates are based on global value, with any error only affecting the Footprint allocation among countries. We believe the maximum distortion for even a small, trade-dependent country would be less than 5%.
4. *Data errors in statistical sources for one particular year.* Error in printed or electronically published data can be spotted by comparison with similar data reported for other years. With our improved ability to automate comparisons across time and across nations, these errors are practically eliminated.
5. *Systematic misrepresentation of reported data in UN statistics.* Distortions arise from over-reported production in planned economies, under-reported timber harvests on public land, poorly funded statistical offices, and subsistence, black market, and non-market (or informal) activities. Since most consumption occurs in the affluent regions of the world, these data weaknesses may not distort the global picture significantly.
6. *Systematic omission of data in UN statistics.* There are demands on nature that are significant but are not, or are not adequately, documented in UN statistics. Examples include data on the biological impact of water scarcity or pollution, and the impact of waste on bioproductivity. Including these aspects would increase the Footprint size.

Some of the above-identified distortions generate margins of error on both sides of the data point, but errors leading to an under-reporting of the global ecological overshoot almost certainly overshadow the other errors. With every round of improvement in the accounts, the use of more comprehensive data sets and independent data sources, the consistency and reliability of data can be checked more effectively, and the robustness of our calculations will improve.

Comparison to other related methods

The most recent Ecological Footprint accounts (Wackernagel et al., 1999) incorporate comprehensive data sources and build on exposure to a number of other approaches. Alternative approaches to the fossil fuel Footprint include the area required to provide renewable energy mix (Ferguson, 1999; Ferguson et al., 2001) and the area required to maintain fossil energy stocks in the lithosphere (Stöglehner, 2003). The publications of Haberl et al. (2001) and van Vuuren et al. (1999) helped refine the potential distortions and confusions arising from the use of 'global hectares.' We sharpened the way they are calculated, basing the equivalence factors now on inherent agricultural suitability instead of actual biomass production (IIASA and FAO, 2000). We also concluded that actual, unweighted hectares are useful for mapping the physical extension of human demands, but that global hectares are necessary to capture a population's demand on, and a region's supply of, Biocapacity in consistent and globally comparable way (Wackernagel et al., 2004a, b).

Van Vuuren et al. (1999) also showed a way to link a country's demand to its area of origin, making demands geographically explicit. With the limited data presently available, only some parts of the nation's Footprint accounts could be expanded to document country-specific trade. By tracing resources to their origins, rather than merely distinguishing domestic production from imported production, the accounts would become far more voluminous. As computer capacity increases and more detailed bilateral trade statistics become accessible, future accounts may trace trade between specific countries (Erb, 2004).

The studies of Lenzen and Murray (2001) as well as Luck et al. (2001) have examined ways to make the Biocapacity aspects of the accounts more sensitive to local ecological conditions. Luck establishes a method to compare urban Footprints directly to the Biocapacity surrounding the city. Lenzen and Murray advocate the need to capture the quality of the impact. Since assessing the quality of impact is more speculative and depends on predictions about future productivity, current accounts focus only on the exclusive use of area, thereby maintaining a conservative estimation of overshoot.

Inspired by the Ecological Footprint, the Wildlife Conservation Society and the Center for International Earth Science Information Network (CIESIN) launched a project to capture the human dominance on the planet (Sanderson et al., 2002). The innovative mapping project captures the extent of human presence on the planet, characterizing 83% of the terrestrial surface as under direct human influence. This includes regions with appreciable levels of land conversion, population density, electrical power infrastructure, and access by roads, rivers, and coastlines. Moreover, this same level of influence extends over 98% of the land able to support rice, wheat, and maize, the world's most vital food crops. Since this project does not measure overuse of areas, it cannot measure overshoot, but does spatially illustrate where human activities threaten wild spaces.

In a similar study using a less permissive definition of human influence, researchers working with the non-profit organization Conservation International found that wilderness areas still cover 46% of the world's land area. The reason this result differs significantly from the 17% reported in the human footprint study is

Conservation International's more lenient exclusion criteria. In contrast to the human footprint, which delineates ecosystems where anthropogenic factors form an important ecological force, *Wilderness: Earth's Last Wild Places* documents regions that retain at least 70% of their original vegetation, cover no fewer than 10,000 km^2, and have fewer than five people/km^2. These wilderness areas, at the margins of human influence, provide conservation opportunities that protect large areas for minimal cost.

These more arbitrary definitions of human influence may be strengthened using measures like human appropriation of net primary productivity (HANPP) that have the ability to evaluate the intensity of human use of ecosystems. This measure's relationship to Ecological Footprint accounts is discussed in detail in Haberl et al. (2004).

Although vast wilderness areas seem at odds with the conclusions of the Ecological Footprint and the human footprint, a closer inspection corroborates all three studies. While 46% of the land surface denoted as wilderness certainly harbors a diversity of life and aesthetic value, it consists to a significant extent of photosynthetically unproductive regions like Antarctica, Greenland, the far reaches of the tundra, and vast dry regions like the Sahara and Australian Deserts. From a natural capital perspective, these regions produce a far smaller share of the planet's capacity to produce the basic sustenance of society—food, fiber, timber—and the valuable service of carbon sequestration. In fact, the Ecological Footprint classifies 36% of the Earth's terrestrial surface as unproductive (and hence barely occupied by human activities)—a figure that approximates Conservation International's assessment of wild areas. But this difference between 46% and 36% also points out that there are some wild and protected areas in highly productive ecosystems, and there exist effective strategies to secure biodiversity conservation that is economically viable and provides protective stewardship to these productive (and hence attractive) ecosystems. Low-intensity or traditional farming such as crofting systems in Scotland or mountain peasantry in the Alps are among the European examples that are now increasingly supported by governmental conservation programs (Wrbka, personal communication).

Conclusion

The Ecological Footprint tracks core requirements for 'strong' sustainability and identifies priority areas for 'weak' sustainability. Its premise is simple: how much area does the human economy need to provide ecological goods and services it uses at a renewable rate? How much area does the planet provide to do so? If the required area exceeds the available capacity, overuse of natural capital ensues, thereby violating the principle of strong sustainability. At the same time, ecological overshoot identifies the liquidation of natural capital, which requires a human-made substitute to preserve the criterion of weak sustainability.

Applied globally, national Ecological Footprint accounts reveal ecological overshoot on the grossest of scales; applied nationally, they describe the sources and sites of overshoot and the liability of national ecological deficits.

The latest iteration of these natural capital accounts provides a level of detail never reached before. This permits current Ecological Footprint accounts to calculate time trends, not just for economic sectors or particular resources, but also for trade relationships between countries. Possible applications are discussed in the follow-up papers published in this issue (Wackernagel et al., 2004a, b).

Complementary measures of societal health and environmental quality (such as discussed in Wrbka et al., 2004), however, are needed to develop a fuller picture of sustainability. Its focus on biophysical flows lends the Ecological Footprint strength as a metric of ecological sustainability and distributional justice, but necessarily avoids the flip side of human well-being. These aspects need to be tracked with separate measures. We would warn against combining these distinct aspects into one single index, since arbitrary aggregation of non-commensurable variables tends to dilute useful information. Hence, the Ecological Footprint avoids confusing human demand on the biosphere with other ecological assessments, or with measures of social well-being or institutional capacity. These are all important parameters for building a sustainable world, each of which need to be illuminated separately since there is no magic formula that defines 'optimal trade-offs' among them. For sustainability, we need to achieve both ecological health as well as social well-being, and achieving one at the expense of the other is inherently unsustainable.

Ecological Footprint accounts measure the area required to supply resources and assimilate waste without compromising the ability of those areas to continue to provide services. Nevertheless, the accounts only approximate the true demand on nature due to several inherent limitations. One limitation is their targeted research question that excludes some aspects that would commonly be associated with impact. For instance, the accounts do not describe the intensity of use, biodiversity loss, or activities that impoverish the ability of an area to keep providing ecological goods and services, such as freshwater pollution from nitrogen runoff. Furthermore, the accounts exclude degradation associated with uncertain analysis or poor data, such as the long-term effect of soil erosion on crop yields. Because of the nature of any accounting, it also contains potential errors as identified in this paper, but we do not see them as a major threat to the validity and reliability of the overall results. In fact, due to the accounts' systematic bias to underestimate Footprints and overestimate Biocapacity, there is a strong case for the claim that ecological overshoot as identified by these natural capital accounts is occurring, and that it is most likely larger than the results document. As such, the Ecological Footprint is a warning mechanism, and a tool to both advance the discussion about ecological limits among scientists, policy-makers, and the public, and to frame the public debate on how to best use nature's 'ecological budget' to secure people's well-being.

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