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Tracking the ecological overshoot of the human economy

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Sustainability requires living within the regenerative capacity of the biosphere. In an attempt to measure the extent to which humanity satisfies this requirement, we use existing data to translate human demand on the environment into the area required for the production of food and other goods, together with the absorption of wastes. Our accounts indicate that human demand may well have exceeded the biosphere's regenerative capacity since the 1980s. According to this preliminary and exploratory assessment, humanity's load corresponded to 70% of the capacity of the global biosphere in 1961, and grew to 120% in 1999.

Accounting for Humanity's Use of the Global Biosphere

The human economy depends on the planet's natural capital, which provides all ecological services and natural resources. Drawing on natural capital beyond its regenerative capacity results in depletion of the capital stock. Through comprehensive resource accounting that compares human demand to the biological capacity of the globe, it should be possible to detect this depletion to help prepare a path toward sustainability.

The purpose of this study is to develop such an accounting framework, and to measure the extent of humanity's current demand on the planet's bioproductive capacity. We build on many earlier attempts to create comprehensive measures of human impact on the biosphere. For example, Vitousek *et al.* (1) used consumption estimates to calculate humanity's appropriation of the biosphere's Net Primary Productivity (NPP). They concluded that the human economy co-opted organic material equivalent to 40% of the NPP of terrestrial ecosystems in 1980. Odum developed a conceptual basis for accounting for energy flows through ecosystems and human economies, but did not produce overall accounts (2). Fischer-Kowalski and Hüttler (3) advanced the concept of "societal metabolism," using material flow analysis as a macro indicator for the environmental performance of societies. The *Global Environment Outlook 2000* (4) and *World Resources 2000–2001* (5) describe human impacts on various ecosystem types in detail, but both reports lack an aggregated summary of the impacts. Others have analyzed the integrity of subcomponents of the biosphere, such as carbon cycles (6), freshwater use (7, 8), and the nitrogen cycle (9), have assigned approximate monetary values to the ecological services that humanity depends on (10), or established frameworks for monetary natural capital accounts for nations (11).

This preliminary and exploratory study demonstrates an aggregated approach to natural capital accounting in biophysical units. A wide variety of human uses of nature are identified, measured, and expressed in units that enable direct comparison of human demands with nature's supply of ecological services.

The calculation results and annotated spreadsheet for 1999 are published as supporting information on the PNAS web site, www.pnas.org.

Our global accounts build on assessments of the "ecological footprint" of humanity (12, 13). Such assessments are based on six assumptions:

1. It is possible to keep track of most of the resources humanity consumes and the wastes humanity generates.
2. Most of these resource and waste flows can be measured in terms of the biologically productive area necessary to maintain these flows (those resource and waste flows that cannot are excluded from the assessment).
3. By weighting each area in proportion to its usable biomass productivity (that is, its potential production of biomass that is of economic interest to people), the different areas can be expressed in standardized hectares. These standardized hectares, which we call "global hectares," represent hectares with biomass productivity equal to the world average productivity that year.
4. Because these areas stand for mutually exclusive uses, and each global hectare represents the same amount of usable biomass production for a given year, they can be added up to a total representing the aggregate human demand.
5. Nature's supply of ecological services can also be expressed in global hectares of biologically productive space.
6. Area demand can exceed area supply. For example, a forest harvested at twice its regeneration rate appears in our accounts at twice its area. This phenomenon is called "ecological overshoot" (14, 15).

Thus, the ecological impact of humanity is measured as the area of biologically productive land and water required to produce the resources consumed and to assimilate the wastes generated by humanity, under the predominant management and production practices in any given year. Not only human demand on nature, but also nature's supply changes over time because of innovations in technology and resource management, changes in land use, and cumulative damage of past impacts.

We recognize that reducing the complexity of humanity's impact on nature to appropriated biomass offers only a partial assessment of global sustainability. It is a necessary, but not sufficient, requirement that human demand does not exceed the globe's biological capacity as measured by our accounts.

The Impact Components

Our accounts include six human activities that require biologically productive space. They are (*i*) growing crops for food, animal feed, fiber, oil, and rubber; (*ii*) grazing animals for meat, hides, wool, and milk; (*iii*) harvesting timber for wood, fiber, and fuel; (*iv*) marine and freshwater fishing; (*v*) accommodating

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Abbreviation: FAO, Food and Agriculture Organization.

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infrastructure for housing, transportation, industrial production, and hydro-electric power; and (*vi*) burning fossil fuel. In each category and for each year of the 40-year time series, we calculate both human demand and existing capacity. Our calculations rely on publicly available government data sources, and use conservative estimates where uncertainties exist.

1. Growing crops requires the most productive land of all. The Food and Agriculture Organization (FAO) estimates that today about 1.5 billion hectares of cropland exist worldwide—1.3 billion hectares of cultivated crops and 0.2 billion hectares of unharvested land that supports temporary pastures and fallow land, failed plantings, and shoulders, shelterbelts, and other uncultivated patches (16).
2. Grazing animals requires pasture. The FAO defines permanent pasture, which currently amounts to 3.5 billion hectares, as "land used permanently (five years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land)" (16). We calculate the demand for pasture for each year by estimating the metabolic requirement of populations of five major classes of livestock: cattle, sheep, goats, equines, and camels. We then subtract dietary needs met from cultivated feeds and crop residues from the total dietary requirement to obtain the amount supplied from grazing.
3. Harvesting timber requires natural forests or plantations. According to the FAO's Forest Resource Assessment (FRA) 2000, there are 3.8 billion hectares of such forest worldwide, which experienced an annual deforestation rate of 0.2% between 1990 and 2000 (17). Before 1990, we estimate past forest area from the FRA baseline with annual deforestation rates (16). We estimate productivities by using tropical growth rates published by the Intergovernmental Panel on Climate Change (IPCC) (18) and temperate and boreal growth rates from the United Nations Economic Commission for Europe's (UNECE) Temperate and Boreal Forest Resource Assessment 2000 (19).
4. Fishing requires productive fishing grounds. Of the total ocean area, the 6% concentrated along the world's continental shelves provides over 95% of the marine catch (20). Assuming that these numbers reflect productivity distribution, this translates into 2.0 billion biologically productive hectares of the earth's 36.3 billion hectares of ocean area. Inland waters make up an additional 0.3 billion hectares. We use FAO fish catch figures, including by-catch (16, 21), and compare them to FAO's "maximum sustainable yield" figure of 93 million tons/year (22). The 93 million tons are then expressed as their primary production requirement (PPR) per hectare, according to the 1996 mean trophic level and by-catch composition of 35 categories of fish, mollusks, crustaceans, and other aquatic animals. Annual landings are calculated by deducting aquaculture from production in these 35 categories, yielding the wild harvest. The harvest is also converted into a PPR and compared with the sustainable PPR, documenting the effect of fishing down food webs, as described by Pauly *et al.* (23).
5. Accommodating infrastructure for housing, transportation, industry, and hydroelectric power results in built-up land. The space occupied by this infrastructure is the least well documented, because low-resolution satellite images are not able to capture dispersed infrastructure and roads. We use an estimate of 0.3 billion hectares, a minimum estimate of the extent of infrastructure worldwide today, and assume that built-up land replaces arable land, as has been documented for the United States (24). We estimate built-up area by consulting data from Tellus PoleStar (25) and the European Union (26).
6. Burning fossil fuel adds CO_2 to the atmosphere. We calculate the area requirement by estimating the biologically productive area needed to sequester enough carbon emissions to avoid an increase in atmospheric CO_2. Because the world's oceans absorb about 35% of the CO_2 emissions from fossil fuel combustion (27, 28), we account only for the remaining 65%, based on each year's capacity of world-average forests to sequester carbon. This capacity is estimated by taking a weighted average across 26 forest biomes as reported by the IPCC and the FAO (18, 28–30). The sequestration capacity will not remain constant in the future. For instance, changed atmospheric CO_2 concentrations and global temperature may increase the eventual saturation biomass level and the rate at which that is approached. Some sequestration and oceanic absorption may even be reversed. Also, CO_2 sequestration rates may decrease as more and more forest ecosystems reach maturity. Eventually afforestation will saturate so that the net rate of CO_2 uptake goes to zero.

Alternatively to the sequestration approach, the area requirement for a fossil fuel substitute from biomass, using current technology, leads to similar or even larger area demands (31, 32). For instance, the equivalent energy from fuelwood grown on forest land with world average productivity would produce roughly the same area, whereas replacing liquid fossil fuel with the same amount of unrefined biomass energy would require an area 56% larger. Because of inconclusive data about the long-term area demand of nuclear power, we include thermal nuclear energy at par with fossil energy.

Aggregating the Impacts

To aggregate the impact components, we adjust the land and sea areas—cropland, built-up land, grazing land, forests, and fishing grounds—according to their bioproductivities, multiplying each land use category by an "equivalence" factor. These factors scale the area of each category of space in proportion to its maximum potential crop yields as estimated in the Global Agro-Ecological Zones (GAEZ) of the FAO and the International Institute for Applied Systems Analysis (IIASA) (33). We use GAEZ to determine the agricultural suitability index (SI) of each major land area: cropland, built-up land, grazing land, and forest. In the case of fisheries, we create an SI by comparing the ability of fishing grounds to provide animal protein with that of pasture. For each year, we determine the equivalence factor of each of the area types by dividing its SI by the global average SI.

The global average area (of a given year) is assigned the equivalence factor of 1. Thus, the actual areas of bioproductive space and those adjusted with the equivalence factors add up to the same global total (see Table 1). Once the human impacts are expressed in such "global hectares," we aggregate them into one number: the biologically productive space required by a given human population. Expressed as an equation:

$$\Sigma P_i \cdot E_i = A,$$

where P is the actual, physical hectares of land (or sea) type i. E is the equivalence factor for the area type i. The equivalence factor weights P based on its productivity relative to one hectare with average biological productivity. A is the area demand expressed in global hectares, as shown in Table 1.

Because land use changes over time, every year has its proper set of equivalence factors. For example, in areas where agriculture has expanded into forest, the suitability index of the usurped area shifts from forests into cropland. Also, the total amount of biologically productive space on the planet has been decreasing through urbanization and soil degradation classified as "strong" or "extreme," meaning unreclaimable at the farm level or

Table 1. Summary of equivalence factors, humanity's area demands, and earth's biological capacity in 1999 (per capita)

		Average global area demand (per capita)		Existing global biocapacity (per capita)	
Area	Equivalence factor, gha/ha	Total demand, ha (per capita)	Equivalent total, gha (per capita)	World area, ha (per capita)	Equivalent total, gha (per capita)
Growing crops	2.1	0.25	0.53	0.25	0.53
Grazing animals	0.5	0.21	0.10	0.58	0.27
Harvesting timber	1.3	0.22	0.29	0.65	0.87
Fishing	0.4	0.40	0.14	0.39	0.14
Accommodating infrastructure	2.2	0.05	0.10	0.05	0.10
Fossil fuel and nuclear energy	1.3	0.86	1.16	0.00	0.00
Total			2.33	1.91	1.91

To make aggregation reflect differences in bioproductivity, areas are expressed in standardized global hectares (gha), which correspond to hectares with world average bioproductivity.

beyond restoration (34). All these effects are included in our accounts through changing equivalence factors over time.

The Biodiversity Buffer

Among many other environmental goods and services (35), the earth's biodiversity supplies resilience and other stability factors to ecosystems large and small. These environmental values stem primarily from the planetary spectrum of species and their populations. The buffering effect is well recognized in principle, although only moderately understood in practice (ref. 36, pp. i–vi and 1–33, and ref. 37). An "insurance policy" approach requires that humanity maintain the largest buffer possible.

Biodiversity protection is highly dependent on the availability of habitats and life support systems. Hence the significance of the recent "hotspots" analysis by Myers *et al.* (38), demonstrating that 25 localities, covering a mere 1.4% of the earth's land surface, contain the last remaining habitats of 44% of the earth's vascular plant species and 35% of species in four of five vertebrate groups. Were these hotspots to be preserved, that would reduce the mass extinction underway by at least one-third.

But the aggregate expanse under outright protection is not the only factor in safeguarding species. Certain areas can be used for human activities while maintaining species habitats. This requires careful management of human interventions, however, especially when they entail intensive land use. It is not possible to determine precisely how much bioproductive area needs to be reserved for the ≈7–14 million species with which people share the planet. Some ecologists and biogeographers have recommended at least 10% of the earth's land surface (39) (and a critical although undetermined amount of the marine realm). Other scientists propose at least 25% (40). The Brundtland Report, *Our Common Future* (41), commissioned by the United Nations after the Rio Earth Summit in 1992, proposed protecting 12% of the biosphere.

Results

For each year since 1961, we compare humanity's demand for natural capital to the earth's biological productivity. The calculation provides evidence that human activities have exceeded the biosphere's capacity since the 1980s. This overshoot can be expressed as the extent to which human area demand exceeds nature's supply: whereas humanity's load corresponded to 70% of the biosphere's capacity in 1961, this percentage grew to 120% by 1999. In other words, 20% overshoot means that it would require 1.2 earths, or one earth for 1.2 years, to regenerate what humanity used in 1999. (Fig. 1 shows the overall results. Fig. 2 provides a breakdown of the overall increase according to the various land and sea use categories.)

Although Fig. 1 presents a situation of overshoot, it does not say anything about how rapidly the natural capital stock is becoming depleted in the process or for how long such depletion, as evident through deforestation, fisheries collapse, or atmospheric CO_2 build-up, can continue.

Reserving 12% of the biologically productive area for conservation, following the Brundtland Report suggestion, moves the crossing-over point from the 1980s back to the early 1970s, and increases the current overshoot from 20% to nearly 40%.

The global average per capita area demand for 1999 adds up to 2.3 global hectares per person (see Table 1). This is significantly lower than the area demands in industrialized countries such as the United States (9.7 global hectares per person), or the United Kingdom and Germany (5.4 and 4.7 global hectares per person, respectively) (42).

Fig. 2 points to the large impact of the use of fossil fuel energy, even under the conservative assumptions of only absorbing 65% of emissions, and using optimistic long-term sequestration rates.

The uneven growth rate in the overall sequestration demand in Fig. 2 reflects changes in energy use influenced by the two oil shocks of the 1970s. The first shock in 1973 stimulated the use of coal with a high carbon intensity, whereas the second one led to the increased use of fossil gas. The global economic recession in the early 1980s may be the primary reason for a temporary flattening of the fossil energy component.

Our accounts measure human impacts that draw on or compromise the biosphere's capacity to regenerate. Consequently, nonrenewable resources are included in the accounts not as depletable stocks but to the extent that their use damages the biosphere. Complete accounts would include all impacts due to mining, processing, and the consumption of those resources, but for lack of data, we currently account only for the embodied energy associated with the use of nonrenewable resources.

We leave out resource uses for which we have insufficient data, such as services from biodiversity, local impacts of freshwater use, or the loss of biocapacity due to the release of solid, liquid, and gaseous waste other than CO_2. Also, in these initial accounts we only include those impacts of the human economy that the biosphere can potentially regenerate. Activities that systematically erode nature's capacity to regenerate are omitted. For example, the biosphere has no significant assimilation capacity for plutonium or PCBs.

Sensitivity analysis reveals the range of possible outcomes by changes in our assumptions. For example, excluding nuclear power from the accounts (which currently include nuclear energy at par with fossil fuel) reduces humanity's area demand in 1999 by 4%. If we account for 100% of the anthropogenic CO_2 emissions, the area demand increases by 27%. Or, if irrigation-induced yield increases are excluded to account for this pressure on freshwater sources, the area demand increases by 12%.

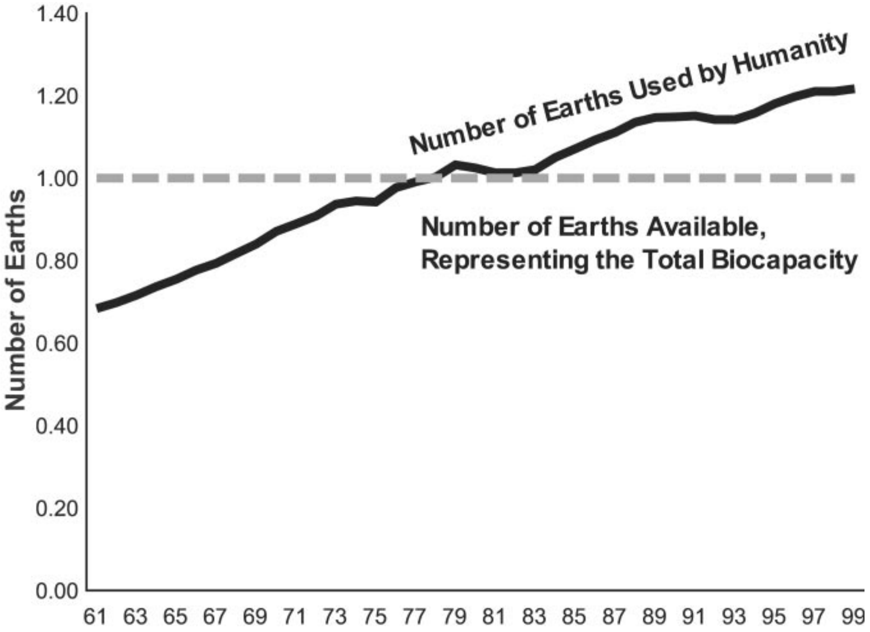

Fig. 1. Time trend of humanity's ecological demand. This graph shows human demand over the last 40 years as compared with the earth's ecological capacity for each year. One vertical unit in the graph corresponds to the entire regenerative capacity of the earth in a given year. Human demand exceeds nature's total supply from the 1980s onwards, overshooting it by 20% in 1999. If 12% of the bioproductive area were set aside to protect other species, the demand line crosses the supply line in the early 1970s rather than the 1980s.

Relevance of These Accounts to Economic Analysis

There are several reasons why aggregate biophysical indicators are useful complements to an economic perspective. First, the current, dominant economic worldview only provides valid guidance if one assumes that all individual actors in the market are well informed. This is, of course, not always the case. Farmers will make mistakes and behave inefficiently, for example, when they are only focusing on economic aspects of their activity and remain unaware of the factors that influence soil erosion and unaware of its consequences to future productivity if it does occur. Although perfect information is never possible, more information is better so long as it is not too costly to obtain and the lack of information affects economic organization (43). The environmental assessment proposed here provides a biophysical indicator of sustainability that, although certainly not perfect, is easy to determine and can help inform production choices.

Second, the standard economic model of resource use over time, the "Hotelling" model (44), assumes that economic actors are informed of the total availability of a resource to be used over time. Staying on the efficient equilibrium path of resource use over time is maintained by economic actors constantly determining, in real resource terms, whether the resource will run out at the time the price of the resource rises to that of a substitute resource and technology. In short, biophysical data are not only required simply for individual production to be efficient, but to keep the market itself on an efficient path over time.

Third, economic theory acknowledges that market prices do not reflect all costs and should therefore be adjusted by the costs borne by third parties, the social costs, including costs to future generations, adjustments referred to as "shadow prices." But to make such adjustments in market prices, economists need biophysical data, such as those presented in this assessment (45).

Fourth, there are many possible sets of efficient prices, even after all third party effects have been incorporated, depending on the distribution of rights to use resources in the first place. Economic values depend on how access rights are distributed between existing people, generating rich and poor individuals or relative equality, as well as generating differences between current and future peoples. It is now well established that achieving sustainability is not simply a matter of including third party effects but of seeing that future generations have sufficient resource rights (46). Decisions with respect to the distribution of rights to resource access need to be made on the basis of biophysical data and ethical criteria, not economic values, for values derive from the distribution, not *vice versa*. Aggregate indicators such as those presented here provide indications of the consequences of the current distribution of resource access within and between generations from which, along with moral criteria, new distributions of rights might be made.

Conclusion

The purpose of these global accounts is not merely to illustrate a method for measuring human demand on bioproductivity, but to offer a tool for measuring the potential effect of remedial policies. For instance, our accounts can be used to calculate the likely effect of various technological breakthroughs, as indicated in the sensitivity analyses referred to above. Emerging eco-technologies producing renewable energy or mimicking biological processes are promising candidates for such calculations. For example, using the best available technology, resource consumption for ground transportation and housing can be reduced by a factor four, while still maintaining the same level of service (47).

Furthermore, resource accounting, as attempted here, could help guide a potential reaction to overshoot. Combined with national or regional assessments presented elsewhere (12, 13, 48–50), our accounts could help determine how much each nation or region is contributing to the overall impact of humanity. And when further refined, they could help evaluate potential strategies for moving toward sustainability.

To our knowledge, no government operates comprehensive

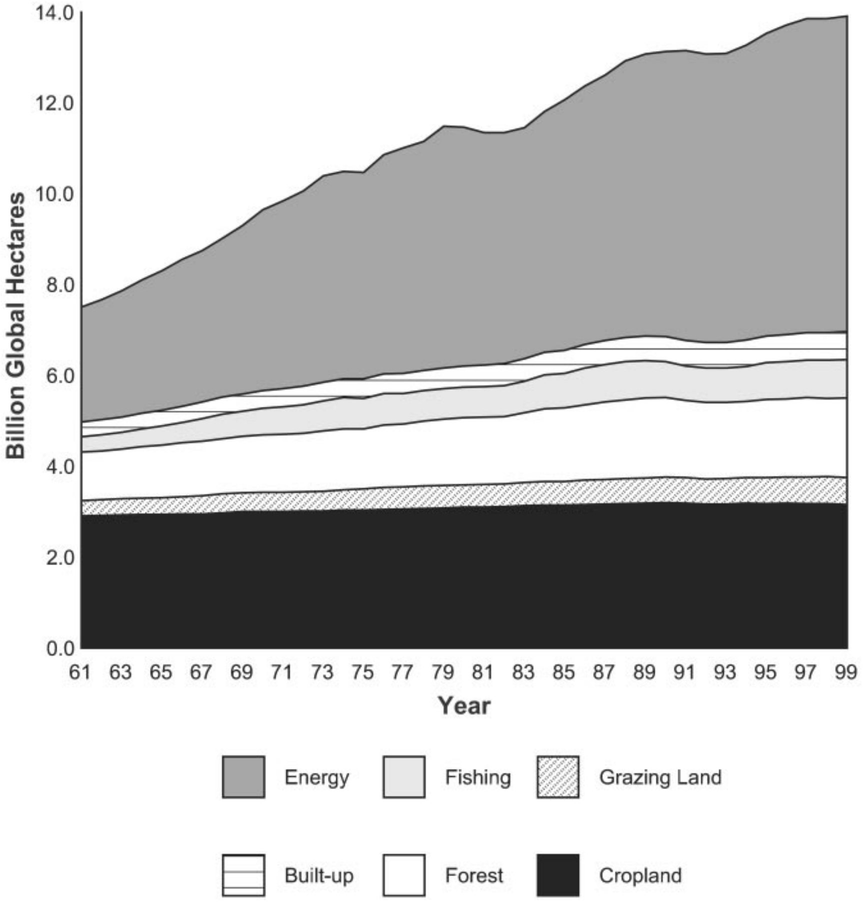

Fig. 2. Global ecological demand over time, in global hectares. This graph documents humanity's area demand in six different categories. The six categories are shown on top of each other, demonstrating a total area demand of over 13 billion global hectares in 1999. Global hectares represent biologically productive hectares with global average bioproductivity in that year.

accounts to assess the extent to which human use of nature fits within the biological capacity of existing ecosystems. Assessments like the one presented here allow humanity, using existing data, to monitor its performance regarding a necessary ecological condition for sustainability: the need to keep human demand within the amount that nature can supply.

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