

REVIEW

Humanity's unsustainable environmental footprint

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Within the context of Earth's limited natural resources and assimilation capacity, the current environmental footprint of humankind is not sustainable. Assessing land, water, energy, material, and other footprints along supply chains is paramount in understanding the sustainability, efficiency, and equity of resource use from the perspective of producers, consumers, and government. We review current footprints and relate those to maximum sustainable levels, highlighting the need for future work on combining footprints, assessing trade-offs between them, improving computational techniques, estimating maximum sustainable footprint levels, and benchmarking efficiency of resource use. Ultimately, major transformative changes in the global economy are necessary to reduce humanity's environmental footprint to sustainable levels.

Since the latter part of the 18th century, humans have been altering the Earth at an unprecedented and unsustainable rate and scale by radically transforming the landscape, increasing natural resource use, and rapidly generating waste. One way of quantifying the total human pressure on the natural environment is to calculate humanity's "environmental footprint"—an umbrella term for the different footprint concepts that have been developed during the past two decades.

Common to all environmental footprints is that they quantify the human appropriation of natural capital as a source or a sink (1–4). The basic building block of footprint accounts is the footprint of a single human activity (Fig. 1). Each specific footprint indicator focuses on one particular environmental concern (e.g., limited land, limited fresh water, and so forth) and measures either resource appropriation or waste generation, or both. The ecological footprint (EF) measures both the appropriation of land as a resource and the land needed for waste uptake (CO₂ sequestration) (5). The first component is separately described as the land footprint (LF) (6, 7); the second component, as the energy footprint (EnF) (8). The water footprint (WF) measures both the consumption of fresh water as a resource and the use of fresh water to assimilate waste (9). The material and phosphorous footprints (MF and PF) focus on measuring resource appropriation alone (10, 11). The carbon or climate footprint (CF) measures emission of greenhouse gases to the atmosphere (12); the nitrogen footprint (NF) measures the loss of reactive nitrogen to the environment (13). The biodiversity footprint (BF) measures the threat of human activity to biodiversity

(14). Footprints are indicators of human pressure on the environment and form the basis for understanding environmental changes that result from this pressure (such as land-use changes, land degradation, reduced river flows, water pollution, climate change) and resultant impacts (such as biodiversity loss or effects on human health or economy).

Environmental Sustainability

Environmental sustainability requires that footprints remain below their maximum sustainable

level, at global scale, and in some cases at smaller geographical scales as well. Sustainability depends on the size and spatiotemporal characteristics of humanity's footprint relative to Earth's carrying capacity. Environmental footprints are closely related to the concept of planetary boundaries—thresholds in Earth-system variables that, if traversed, could generate unacceptable change in the biophysical processes of the planet's natural environments (15). Environmental footprints measure how much of the available capacity within the planetary boundaries is already consumed.

The EF asserts that human appropriation of bioproductive area exceeds available biocapacity by 50% (16). The message that humanity is hence using one-and-a-half planets is one of the reasons that the EF concept has become a popular and effective tool to communicate unsustainability. It has further been estimated that humanity's blue WF, referring to consumption of surface and groundwater resources, exceeds the maximum sustainable blue WF during at least parts of the year in half of the world's river basins (17). Based on an analysis of nitrogen and phosphorus emissions to water, the gray WF—the WF component referring to water pollution—was found to exceed the maximum sustainable gray WF (assimilation capacity) in about two-thirds of the world's river basins (18). The global CF should be reduced by 60% (from 50 to 21 Gt CO₂-equiv./year) between 2010 and 2050 to achieve the climate target of a maximum 2°C of global warming (19).

For each type of environmental footprint there is a maximum sustainable level, but quantitatively

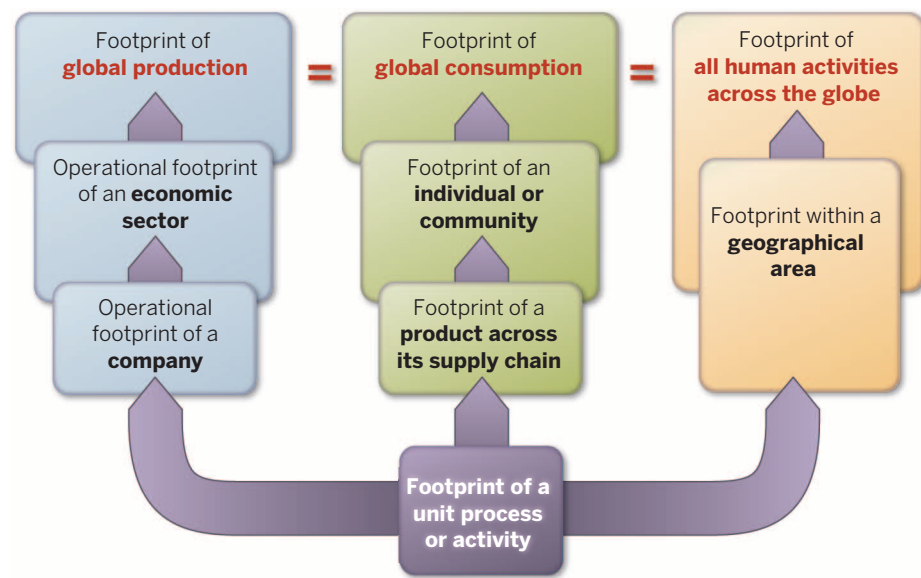


Fig. 1. The relation between footprints of different entities. At the basis of any footprint account are mutually exclusive unit footprints. A "unit footprint" is the footprint of a single process or activity and forms the basic building block for the footprint of a product, consumer, or producer or for the footprint within a certain geographical area. The footprint of global production is equal to the footprint of global consumption. Both equal the sum of the footprints of all human activities across the globe.

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defining these levels is in its infancy (Fig. 2). Proposed maximum levels are confounded by uncertainties, ambiguity, and subjectivity. As an example of large uncertainties, the maximum sustainable level of the blue WF has been estimated to be 1100 to 4500 km³/year at the global scale (20). Ambiguity exists, for example, regarding the maximum sustainable CF: Usually it is expressed as a maximum volume of Gt CO₂-equiv./year, but it has been suggested that cumulative emissions over time form a better indicator for the ultimate resultant global warming (27). Finally, subjectivity in setting maximum sustainable levels is an intrinsic part of the human decision-making process, exemplified by the maximum global warming threshold of 2°C, which was reached as a consensus (22).

At the global level, the environmental footprint of human beings shows an uninterrupted increase during the past century, owing to growing population, increasing affluence, changing

consumption patterns (e.g., more meat in diets), and increasing mobility. In the period 1961 to 2008, the EF more than doubled (16). The blue WF grew by a factor of 5.6 in the period 1900 to 2000 (23), and the total amount of reactive nitrogen created by human activities (the NF) has increased ninefold during the 20th century (24). Global carbon emissions from fossil fuels—part of humanity's CF—increased even more: by over 16 times between 1900 and 2008 (25). Developing countries have now overtaken developed countries in both total territorial and total CF emissions (26). With business as usual, all footprints are expected to further increase during the coming few decades, rather than decrease toward sustainable levels (19, 27, 28).

Resource Efficiency and Producers

Producers compete for natural resources (e.g., land and water rights) and for their share in the limited assimilation capacity of the Earth (e.g.,

carbon emission and wastewater discharge permits). To get the highest benefit per unit of natural resource consumption and unit of pollution, footprints of activities and products need to be minimized. The environmental footprint has become a key performance indicator in environmental management and a way to demonstrate corporate social responsibility (29, 30). Resource efficiency means a small footprint per unit of product.

The footprint of a company consists of direct (operational) and indirect (supply-chain) components. The footprint of a final product depends on the footprints of the processes in the supply chain of the product (Fig. 3). In practice, companies tend to formulate reduction targets regarding their direct footprint, thereby ignoring their indirect footprint, which is often much bigger (31). The indirect WF of beverage companies, for example, can constitute about 99% of their total WF (32). Recent developments in footprint standardization address this issue. For instance, the Corporate Value Chain (Scope 3) Accounting and Reporting Standard of the Greenhouse Gas (GHG) Protocol (33) provides guidance for companies and other organizations to report GHG emissions from all supply-chain, operational, and disposal activities (the “value chain”) associated with their business. A major challenge remains in companies setting reduction targets for their supply-chain footprint. Current research focuses on the practicality of data compilation and reporting, the completeness of supply-chain coverage, and the accuracy and transparency of results (29, 34). These issues need to be addressed to enable meaningful comparisons between companies and benchmarking based on best available technology and practice (32, 35). Another challenge is to internalize the costs related to the environmental footprint of products in their price—for example, by charging carbon and water taxes along the supply chain, or a general environmental tax on final products (e.g., a tax on meat). Yet another challenge is to develop a better understanding of trade-offs between different footprints. Reducing the CF by moving toward bioenergy, for instance, will inevitably increase the LF and WF (36). Reducing the WF in overexploited river basins by large-scale interbasin water transfer or by increasing food imports will inevitably increase the energy footprint.

Social Equity and Consumers

An individual's or community's consumption behavior translates into an environmental footprint. Given the huge variation in consumption patterns and related environmental burdens and the world's limited natural resources and assimilation capacity, an increasingly pressing question is who takes the biggest part of the pie, and what actually is a “fair share.” Social equity implies fair sharing of limited natural resources among countries and between people within countries.

The EF of the average global citizen is 2.7 global hectares, while that of the average U.S. citizen is 7.2 (16). If all world citizens would have an EF

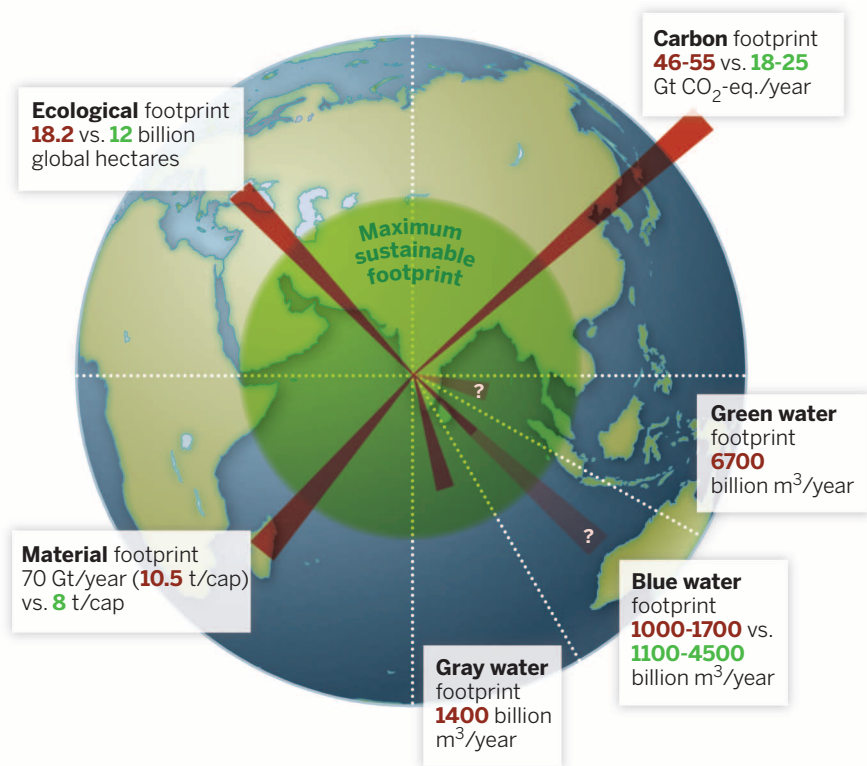


Fig. 2. Estimated global footprints versus their suggested maximum sustainable level. The inner green shaded circle represents the maximum sustainable footprint [compare (15)]. Red bars represent estimates of the current level of each global footprint. The EF of 18.2 billion global hectares (in 2008) exceeds the maximum sustainable EF of 12 billion global hectares by about 50% (16). The green WF has been estimated at 6700 billion m³/year (average for 1996 to 2005) (9); a reference level is not yet available. Blue WF estimates vary from 1000 to 1700 billion m³/year (9, 57) and should be compared to the global maximum sustainable blue WF of 1100 to 4500 billion m³/year (20); data on maximum blue WFs per river basin and month are provided by (17). The gray WF has been conservatively estimated at 1400 billion m³/year (average for 1996 to 2005) (9, 57); in two-thirds of the world's river basins, the pollution assimilation capacity for nitrogen and phosphorus has been fully consumed (18). The CF of 46 to 55 Gt CO₂-equiv./year (in 2010) exceeds by more than a factor of 2 the estimated maximum sustainable CF of 18 to 25 Gt CO₂-equiv./year, which must be achieved by 2050 if the maximum 2°C global warming target is to be met (19). The MF has been estimated at 70 Gt/year [10.5 ton/cap in 2008 (10)], and a reduction to 8 ton/cap has been suggested as a sustainable level (58).

equal to the latter, the global EF would exceed Earth's biocapacity not only by the average factor of 1.5, but by a factor of 4. The current WF of the average U.S. consumer is two times the global average (9). To ensure that the WF of humanity as a whole will not grow under the United Nations medium population scenario, the average WF per capita will have to decrease from 1385 m³ in 2000 to 910 m³ in 2050 and 835 m³ in 2100 (32). If we assume an equal WF share for all global citizens, the challenge is to reduce the WF over the 21st century by 22.5% for consumers in China and India and by 70% for consumers in the United States. The CF of the average U.S. consumer has been estimated to be 5.8 bigger than the global average (37). Footprints per capita hugely differ not only across, but also within nations (38). Equitable consumption in a finite world requires "contraction and convergence": The environmental footprint of humanity has to reduce toward sustainable levels, and footprints per capita have to converge to similar, more equitable shares (32, 39).

Footprints per capita are determined by two factors: consumption pattern and intensity of natural resource use or waste generation per unit of product consumed (32). Consumers can influence the latter by buying products with high eco-efficiency (low footprint), but often this is hampered by a lack of product information. Usually, the only relevant type of information refers to the energy efficiency and sometimes the water efficiency of products. Consumers can also reduce their footprint by changing their consumption behavior. Measures that have the

potential to contribute most to the reduction of the environmental footprint—at least in industrialized countries—include replacing animal with crop products (40, 41), reducing food and other waste (40), saving energy at home and in transport (42), and buying second-hand, recycled products and low-footprint, dematerialized "services" rather than primary-material-based goods (39). However, such behavioral changes are difficult to achieve in reality because of social constraints and lock-ins (43). Another problem is that improvements in resource efficiency often do not result in the expected saving, since they allow overall consumption levels to increase—the so-called rebound effect (44). Profound, effective, socially accepted, and long-lasting changes as required for a truly sustainable transition have yet to occur.

Resource Security and the Influence of Politics

Resource security for governments means limiting national dependency on footprints that are difficult to control or influence. For companies, it means limiting corporate dependency on risk-increasing footprints in the supply chain. International trade plays an important role in this instance because it inherently shifts environmental burdens from the place of consumption in one country to the place of production elsewhere in the world. This effect of international externalization is well documented by studies of national footprints (6, 7, 10, 14, 32, 45). In the United Kingdom, for example, ~40% of the CF of national consumption lies abroad (37) and so

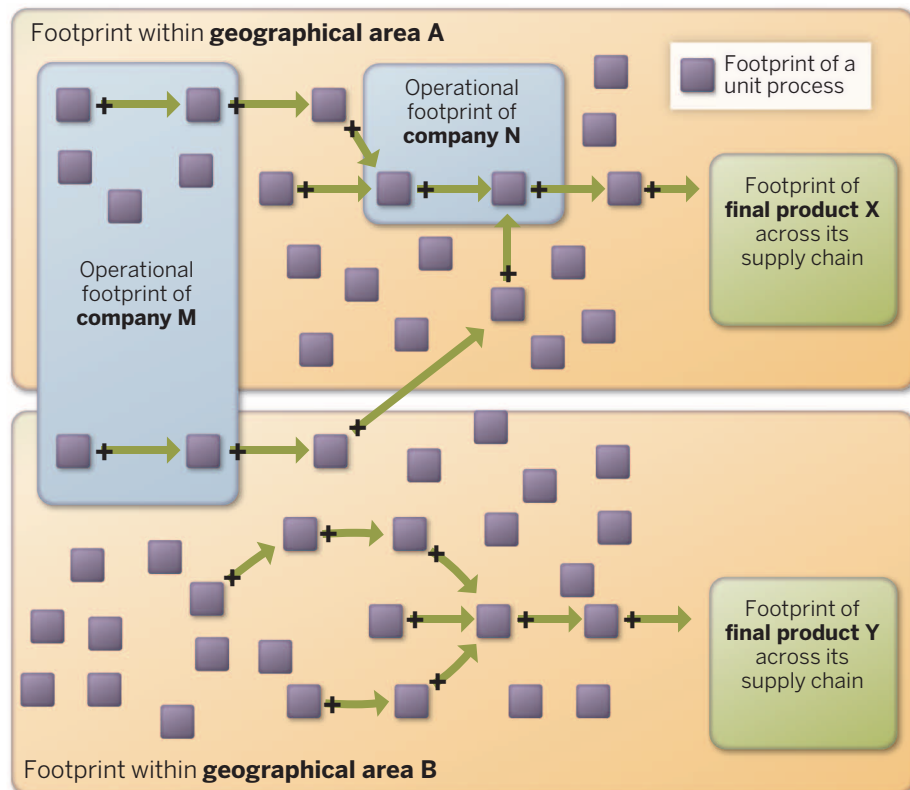
does 75% of the WF (9). Worldwide, 24% of the LF is embedded in international trade (7), as is 22% of the WF (9), 26% of the CF (45), and 41% of the MF (10). Policies aimed at increasing the sustainability of consumption therefore need to take into account and target production technologies employed abroad. Because full national self-sufficiency is generally neither possible nor desirable, international cooperation on reducing the footprint of production worldwide is the only path available to tackle unsustainability at the national scale.

This becomes evident when looking at natural resource stocks (fertile land, fossil fuels, fossil groundwater, materials) and flows (river runoff, renewable groundwater, wind and solar energy). These resources occur locally, but they have become global commodities from an economic standpoint (46). Comparing the environmental footprint of national consumption with its natural endowment base allows one to identify inherent and possibly critical resource dependencies (10, 46). Surprisingly, countries like India and China that have EFs and WFs exceeding their sustainably available land and water resources are still net exporters of embodied land and water (7, 9). Sustainable production is here at odds with the interest of export earnings.

Even though the environmental footprint of humanity is ultimately driven by consumption, governments invariably focus on "eco-efficiency" (low footprints per unit of production), leaving consumption volumes and patterns unaddressed. An example of well-intended but noneffective policy was the Kyoto Protocol that set reduction

Fig. 3. Footprint accounting over supply chains.

The footprint of a product is the sum of the footprints of the processes along the supply chain of the product. These processes may take place in different geographical areas. The operational footprint of a company is the sum of the footprints of its own operations. For simplicity, one-directional supply chains are drawn; in reality, supply chains of different products are interwoven and partly cyclic. Footprint-allocation procedures are applied to avoid double counting.



targets per country with respect to GHG emissions generated within the country. Relocation of production from developed to developing countries over time resulted in “carbon leakage,” i.e., shifting of emissions to countries outside of the agreement’s control. Even though industrialized countries could implement emission-reduction projects in other countries, this did not lead to actual reductions in national carbon footprints (45). In the case of setting caps on WFs by river basin, likely the same will happen: Water management is typically territorial-based and focused on increasing water-use efficiency, not related to the total volume of consumption (32). Efficiency may thus increase, but demand for water-intensive commodities such as meat and biofuels is rapidly rising, as well. Until this dichotomy is addressed, sustainable consumption remains a blind spot in policy-making.

Short-term resource security is still of greater interest to most governments and companies than the long-term sustainability of supplies and their consumption. This can be explained by the time frames for economic returns and political cycles. Increasingly, countries try to secure their food supply through land and water “grabbing” elsewhere (47). Similarly, several countries can only meet their biofuel targets through increasing imports (48), with associated land and water footprints elsewhere (49, 50). Long-term resource security requires that imports and supply chains are truly sustainable. This is where national environmental footprint accounting can help to inform policies aimed at sustainable production worldwide.

Future Prospects

Supply-chain evaluation has only recently become an issue in corporate CF accounting, whereas it has always been a strong component of the WF. We envisage a future in which the different footprints become equally important, get elaborated to the same level of detail, and are applied by companies and governments to measure environmental performance in both operations and supply chain. We expect that footprint benchmarks will be developed for unit processes and final products as exemplified for the EnF (51) and the WF (32).

Methodologically, we expect cross-fertilization among the different footprint concepts and the gradual evolution of a consistent analytical framework with broad but not overlapping coverage of environmental pressures (4). Common questions to be solved across all footprints include the difficulty of tracing along supply chains, how to avoid truncation, how to allocate to multiple products from one process, and the assessment of uncertainties. Further study is required in harmonizing footprint assessment methods, which focus on quantification of environmental pressure and assessment of sustainable, efficient, and equitable resource appropriation (5, 32), and life-cycle assessment methods, which focus on quantification of environmental impacts (52, 53). At a more fundamental level, a continued debate is necessary between scholars in environmental

footprint assessment (EFA) and those who criticize the new field for inaccuracy and simplification (54). Work remains to be done also in embedding EFA in dynamic, integrated assessment models to better understand how complex processes of global change ultimately affect the natural environment and human development.

To reduce humanity’s environmental footprint toward a sustainable level, it is necessary to reach consensus on footprint caps at different scales, from global to national or river-basin scale. Footprint caps need to be related to both production and consumption (32, 55). The various components of the environmental footprint of humanity must be reduced to remain within planetary boundaries. Improved technologies (eco-efficiency) alone will not be sufficient to reach this goal; consumption patterns will need to alter as well (39). How such cultural shift and transformative change in the global economy could take place remains an open question. It is clear, however, that such change will profoundly affect all sectors of the economy. There are always several entities playing a role in causing a footprint: the investors, the suppliers, the recipients, and the regulators. Hence, the responsibility for moving toward a sustainable footprint is to be shared among them (32, 56). The way societies and economies have institutionalized responsibility is clearly insufficient to warrant environmental sustainability, eco-efficiency, fair sharing, and long-term resource security. Exploring how we can better institutionalize full supply-chain responsibility is one of humanity’s major research challenges toward achieving a sustainable future.

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10.1126/science.1248365