Ecological Footprint accounting can be applied to any scale, from the planet down to an individual or a product. By mapping the size of an economy's physical metabolism, compared to what nature can renew, it provides an important input for decision-makers concerned with making economic success last. Through the many applications of the tool, the method has also met with criticism. Both the range of applications as well as the raised criticisms are discussed in this chapter.

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Ecological Footprint accounts

Criticisms and applications[1]

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1. Introduction

With the emergence of the sustainable development debate and the increasing attention to global warming, food security and environmental degradation, the question of the scale or size of the human economy compared to its host planet has become more prominent. While theorized about in economic debates such as Herman Daly's "Steady State Economics" (1973. 1977) or modelled in early computer simulations on systems dynamics such as World3 which underpinned *Limits to Growth* (Meadows et al., 1972), discussions on how to limit or even reduce the metabolism of current economies has become widespread. The latest five-year plan of China is advocating Ecological Civilization (The People's Republic of China, 2015). One hundred and ninety countries have signed the Paris Climate Agreement asking for reducing carbon emissions to an extent that climate would not warm beyond 1.5° or 2° C. The UN Sustainable Development Goals urge the world to operate within the ecological possibilities of our ecosystems (UN, 2015).

The Ecological Footprint is an accounting system that sheds light on the size of economies' material metabolism by answering one particular question: *How much of the biosphere's (or any region's) regenerative capacity does any human activity demand?* This is a relevant question because sustainable development or long-term economic success depends on keeping humanity's material demands within the amount the planet can renew (Wackernagel et al., Chapter 16). In this chapter we first highlight some applications and then address criticism that Ecological Footprint accounting has received.

2. Scales of Ecological Footprint assessments and their policy relevance

Ecological Footprint and biocapacity assessments can be applied at any scale.[2] Biocapacity can be calculated for a particular plot of land, a region or the entire biosphere. Footprints can be assessed for any activity at any scale, be it for a single activity, the lifestyle of a person, a city, a nation or even humanity as a whole. Note though that organizations do not have a Footprint per se, since they are not clearly defined entities. However, organizations' activities have Footprints. Hence when analyzing resource demands of organizations, the inquiry has to start by defining which organizational activities are being analyzed.

Ecological Footprint accounts, like any accounting system, are documenting the past and are limited by global data availability, mainly UN data sets. In 2017, the Ecological Footprint accounts have the ability to provide data for over 200 nations for 53 years (data sets correspond to 1961–2013, Global Footprint Network, 2017). All results are available on the open data platform at data.footprintnetwork.org. The historical time series help inform discussions about likely future trends. Additionally, any scenario outputs can be translated into Footprint and biocapacity outcomes (Moore et al., 2012).

The Ecological Footprint is a diagnostic tool that can be used to inform decision-makers of their current position in comparison to other nations of the world. While this tool cannot tell policy-makers what exactly to implement, it can identify key problem areas and potential options for increasing an economy's resource security. Similar to financial bookkeeping, Footprint accounts provide the context for decision-making, not prescribed solutions. This principle applies at all levels of analysis, including the personal level. For instance, a variety of Footprint Calculators have been developed, including one by Global Footprint Network (www.footprintcalculator.org) geared towards individuals, which offer diagnostics to inform decision-makers about potential actions to take. These 'yardsticks' for resource use can help people make better choices.

One particular value that the national data sets provide, as available through the data.footprintnetwork.org data platform, is the ability to compare the economic and political history of countries to their biocapacity and Footprint trends. Common patterns can be analyzed to distinguish which socio-economic developments may have been shaped by its resource contexts or to what extent economic and political changes shifted the resource availabilities for societies (Niccolucci et al., 2012).

The power of the Ecological Footprint is often recognized for its ability to communicate to wide audiences (Costanza, 2000; Deutsch et al., 2000; Stiglitz et al., 2009). However, this often also leads to the criticism that it promises too much. If the user understands the research question behind the concept, the meaning of the results should be fairly clear. While the wider public may not know the exact research question driving Ecological Footprint accounting, essentially ‘how much nature people use compared to how much there is’, the interpretation of ‘how many planet Earths would it take if all of humanity lived your lifestyle’ is a clear and accurate reflection of what Ecological Footprint accounts compute.

3. The link between Ecological Footprints and sustainable development

Many users misunderstand the Ecological Footprint as a measure of sustainability. As pointed out by the Footprint standards (www.footprintstandards.org), the Footprint is more accurately described as a metric of ‘unsustainability’. For instance, if humanity’s Footprint is larger than the world’s biocapacity, humanity is in an unsustainable state. The Footprint and biocapacity metrics describe a necessary condition for sustainability, not a sufficient one. In this section, we further describe the link between Ecological Footprints and sustainable development.

Sustainable development implies a commitment to giving all people the opportunity to lead fulfilling lives within the means of planet Earth. This kind of development continues to be identified as the primary overarching policy goal, as exemplified most recently by the UN’s Sustainable Development Goals, as well as the OECD’s Green Growth strategy, and in the ‘Green Economy’ debate stemming from Rio+20 (2012). Yet when it comes to actual environmental strategies and policies, are decision-makers asking the right questions to lead us towards this goal? Over the last decades, the global sustainable development debate has been unfocused. Definitions abound, and long agendas are drawn up in international forums that lack specificity and consistency with the reality of planetary limits. This lack of clarity is surprising, since the much earlier 1972 United Nations Conference on the Human Environment in Stockholm ran under the theme 'Only one Earth'.

The current lack of specificity and consistency could be overcome with science-based benchmarks and quantitative tracking. Sustainable development, after all, builds on the UN's original focus: economic and social development (as expressed in UNDP, 2011, the *Millennium Development Goals*, 2000, or the UN's 1948 Universal Declaration of Human Rights), and it is complemented by the adjective 'sustainable', recognizing that this development has to fit within our one planet. Sustainable development therefore becomes the marriage of these two dimensions: 'sustainable' and 'development'. The interplay between these two dimensions – the human development goal and the environmental boundary condition – is also at the heart of the Brundtland Commission's sustainable development definition. Their approach postulates to meet current needs without compromising the ability of future generations to meet their own needs (WCED, 1987).

By emphasizing the two dimensions of sustainable development, it becomes possible to track the concept through a science-based measurement framework (Boutaud, 2002a, 2002b; Moran et al., 2008). By 'science-based', we mean that the two objectives, 'sustainable – or does it fit within the confines of one planet?' and 'development – are human lives becoming measurably better?' can be tracked through evidence-based outcome metrics. The first dimension, 'sustainable', or to what extent such development can be supported within the means of planet Earth, is measured by the ratio between Footprint and biocapacity. The second dimension, 'development', depends on how progress is interpreted, and what the key outcomes are that determine such progress. One of the most prominent outcome measures of development, particularly for comparing nations, is UNDP's Human Development Index (HDI). They are described in detail below.

Sustainable development occurs at the intersection of these two dimensions. A first necessary condition for living within the means of nature occurs if the Footprint is within the available biocapacity. Currently, there are 1.7 global hectares of biocapacity available on the planet per person, but some of that biocapacity is also needed to support wildlife. The Ecological Footprint therefore compares a population's demand on the Earth's resource against the Earth's or a region's biocapacity (that is, its ability to regenerate resources and ecosystem services). Second, UNDP considers an HDI of more than 0.7 to be 'high human development'. Now being used by organizations such as WWF, the World Business Council for Sustainable Development (WBCSD, 2011), the UNEP's Green Economy initiative, this two-dimensional framework, breaks down sustainable development into its core components: a commitment to human well-being, and development within the means of planet Earth.

The resulting global graph provides a high-level snapshot view of countries' or populations' current development position.[3] It can also be used to show progress over time, to compare the situation of one community with another one, or to illustrate patterns.[4] Figure 33.1 depicts countries and exemplifies the challenge of creating a globally reproducible resource demand which also secures a high level of human well-being. In other words, they produce thriving lives at a Footprint level that all people could replicate without overtaxing the planet's ecological resource base.

This framework can also be used to analyze the recently launched Sustainable Development Goals (SDGs). When SDG achievement is measured by the Bertelsmann SDG index (Sachs et al., 2016) and compared against these sustainable development outcomes, it becomes evident that high performance on SDGs correlates with higher HDI, but also with higher Footprints. In other words, SDGs may not be formulated with sufficient focus on resource security to keep powering the development (Wackernagel et al., 2017). If this indeed proves to be the case, SDGs as formulated today could therefore put the long-term opportunities for sustainable human development at risk.

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Figure 33.1 Mapping sustainable development outcome: HDI and the Footprint of nations, in 2013. Global sustainable development is assessed using UNDP's Human Development Index (HDI) as an indicator of human development, and the Ecological Footprint as a measure of human demand on the biosphere (based on the 2017 edition). The presented results reflect the situation in 2013 (UNDP, 2016). An Ecological Footprint significantly less than 1.7 global hectares per person makes those resource demands globally replicable (it would need to be significantly less, as the deficit would also need to provide for wildlife). Despite growing adoption of sustainable development as an explicit policy goal, most countries do not meet both minimum requirements. Since every country has different amounts of biocapacity within its national boundaries, this analysis can also be adapted to each country. Also: note that the world as a whole is outside the global Sustainable Development quadrant.

Making sustainable development measurable will not only accelerate the global debate, but it will also provide decision-makers with a robust metric to support them in exploring potential trade-offs and options. The simple, empirical framework proposed here could empower nations as it identifies risks to their own performance. Therefore, it represents neither conditionality nor an approach that requires international agreements. It simply recognizes that human development depends on access to ecological assets and the resources and services they provide. Ecological Footprint accounts provide insight, enhance foresight and stimulate needed innovation.

4. Common questions and misconceptions

Ecological Footprints are subject to several misconceptions, which we cover in this section. Some people misunderstand the measure, or believe that it covers aspects that are not actually calculated in these accounts (for example, some might believe that the Footprint is a pollution measure). There is also confusion between the idea of the Footprint and its actual execution, which is limited by available data. We also address a number of common issues raised in the academic and policy literature. These issues are taken from the Stiglitz Report (Stiglitz et al., 2009); Eurostat (Schaefer et al., 2006); Best et al. (2008); Kitzes et al. (2009); van den Bergh and Grazi (2010); Grazi and van den Bergh (2012); Giampietro and Saltelli (2014); Goldfinger et al. (2014); Galli, Giampietro et al. (2016); and Blomqvist et al. (2013).

Is the term ‘Ecological Footprint’ misleading?

Ecology is the study of nature’s household. One significant lens of the science of ecology is tracking the metabolism and energy flows of nature. That’s what ‘ecological’ refers to in ‘Ecological Footprint’. Further, most of nature is heavily disturbed (or shaped) by human activity. However, since the field of ecology is so vast, there is the potential that the name ‘Ecological Footprint’ could be misunderstood. This is why Global Footprint Network emphasizes that ‘Ecological Footprint’ is a name for a particular research question: how much biocapacity is demanded by a given human activity? It is the research question that counts when analyzing the concept, not the name. Yet it is now a widely used phrase that is intuitive and that many people can readily understand. The name 'Footprint' reflects 'area demand' as in 'footprint of a satellite' or 'footprint of a building'.

The originators of the Footprint (Bill Rees and Mathis Wackernagel) as well as Global Footprint Network have deliberately not trademarked the term, making it available for public use. To protect its integrity, Global Footprint Network has developed standards and has created a partner network that is committed to using the term 'Ecological Footprint' consistently. The more that large institutions such as WWF, WBCSD, UNDP, UNEP or EEA use the term consistently, the less confusion is generated.[5]

Why focus on biocapacity?

The Ecological Footprint tool is built upon the premise that the quantity of human and non-human life on this planet is limited by the biosphere's regenerative capacity. This limitation also includes access to non-renewable resources from the lithosphere. For instance, the use of today's primary lithosphere resource, fossil fuel, is most restricted by the planet's biocapacity – not by underground availability. The biosphere has a limited capacity to absorb waste from fossil fuel use (more specifically, the CO_2 emissions released when fossil fuels are burnt). In other words, if humanity burned all the fossil fuels already discovered, the carbon concentration in the atmosphere might grow beyond 1700 ppm (UK Institution of Mechanical Engineers, 2009).[6]

Conversely, if CO_2 emissions were restricted to the 450 ppm CO_2 concentration threshold in the atmosphere (which many climate scientists consider to be too high for securing ecosystems stability (Hansen et al., 2008; Lovejoy, 2008), then humanity has already found five times more fossil fuels in the ground than can be burned (Leaton, 2012). The divergence between the carbon that humanity has found in the lithosphere and the carbon that can be 'safely' released into the atmosphere makes it clear that waste absorption is the limiting factor for sustainable fossil fuel use, not supply.

Ores are another resource from the lithosphere, largely used to provide society with metals. Unlike fossil fuels, metals are used, not used *up*. Society may need more metals, or metal in use erodes and gets dispersed. Therefore, the use of metals depends on humanity's ability to concentrate the elements. Given existing technology, this ability is largely limited by energy inputs. However, since the majority of industrial energy is sourced from fossil fuels, the limiting factor ultimately becomes biocapacity for ores as well.[7]

In a time of increasing ecological constraints, the research question behind Ecological Footprint accounts could be the most critical one for the twenty-first century. More importantly, it is one that humanity cannot afford to ignore. Failing to live within nature's budget will eventually lead to ecological bankruptcy and societal collapse. Thus there may be no research endeavour more important than building an accurate understanding of humanity's demand on the biosphere. Answering such a research question therefore requires an open, transparent and replicable process, based on empirical evidence. In other words, solid answers depend on rigorous scientific inquiry.

Why measure biocapacity in 'global hectares', and not in TW or tonnes of carbon?

The sun powers planet Earth with about 175 000 terawatts (TW) of solar energy. This translates into as little as about 100 TW of biomass production in the biosphere, terrestrially and in the ocean (100 TW according to Nealson and Conrad, 1999; 75 TW according to Haberl et al., 2007). Possibly close to half of the biocapacity of the planet might be used for food production (Global Footprint Network 2017 National Footprint Accounts), meaning that this biomass production, plus significant fossil fuel input (approximately 2–3 TW of fossil fuel for the food portion of human consumption), turn into less than one TW of food (10 000 kilo joules/day per person times 7+ billion people).

This example illustrates a long energy cascade, along which less and less energy is available, and the remainder is dissipated as energy waste. In other words, no energy is lost, but the quality of the energy (or its exergetic value) is; as a result, along the cascade, less and less energy becomes available. For this reason, expressing flows of biocapacity in terms of energy, or more precisely energy flows (such as TW), while scientifically valid, is difficult for both communication as well as scientific work, since one TW means something very different along the energy cascade – by orders of magnitude. Every TW would need to be described by 'what kind of TW?' Direct comparisons of results would become challenging and potentially confusing.

An alternative is to express biocapacity in terms of biomass production. In ecological sciences, this is called Net Primary Productivity (NPP). Much of the Ecological Footprint work is inspired by such assessments as, for instance, the one by Vitousek et al. (1986) and the many highly interesting and more detailed studies by the Social Ecology group in Vienna guided by Fischer-Kowalski and Haberl (Fischer-Kowalski and Haberl, 1993, 1997, 2007; Haberl and Schandl 1999, Haberl 1997; Haberl et al., 2002). A number of papers have described the link and differences between Ecological Footprint accounting and approaches such as HANPP (human appropriation of net primary productivity) – see for instance Haberl et al. (2004) and Moffatt (1999).

Focusing on one segment of the energy cascade (i.e., where sunlight is transformed into biomass) makes NPP or Footprint studies sharper, and less prone to confusion between different types of joules along the energy cascade (or more precisely, joules of different entropic value) than general studies of energy flows. Yet NPP studies faces two other challenges compared to Footprint accounting:

1 How can we meaningfully compare one ecosystem to another? For instance, crop areas are not managed for producing maximum NPP, but rather to produce maximum amount of the desired crop. The same area of cropland left as a forest might produce significantly higher NPP than the wheat field it currently hosts. Potential NPP helps to compare various biologically productive surfaces more meaningfully – even though it is difficult to measure since it depends on assumptions and extrapolations – but these can be tested against empirical evidence. Therefore, potential NPP results, if robust global data sets were available, would be an important improvement to Ecological Footprint accounts, as they would lead to more robust estimates of equivalence factors (as discussed in more detail below).

2 An even more significant challenge is the difficulty for NPP assessments to compare supply and demand. For instance, in a forest, which parts need to be included in the assessment of availability: tree trunks, obviously, but what about branches? Leaves? Soil? Undergrowth such as ferns, bushes and mushrooms? Roots? How then is demand assessed? Does it include the branches of a tree, even though they are left back in the

forest after harvest? What about the leaves, the disturbed undergrowth, the roots of the cut tree? How can the ‘harvestable limit’ be defined?

The Ecological Footprint’s agricultural perspective, while more limited and mechanical than an assessment of an ecosystem’s entire NPP, makes the demand and supply comparison more direct. For instance, foresters can estimate the timber increment a forest generates, and inversely, the number of cubic metres of timber that are removed from a forest can also be measured.

For these reasons, expressing demand on the biosphere, and availability of regenerative production of the biosphere in agricultural terms, in terms of biologically productive surfaces, allows researchers to assess, with some degree of accuracy, human demand against nature’s supply. And luckily, the measurement units of such an analysis are also easy to understand by a wide public, thanks to the visual power of surface.

Are the equivalence factors adequate?

Equivalence factors attempt to compare hectares across various land uses. They are needed for consistent aggregation of biocapacity. Equivalence factors translate the area of a specific land-use type available or demanded into units of world average biologically productive area (expressed in global hectares). Thus, they vary by land-use type and year. Ideally, the equivalence factors should reflect the ratio of the maximum potential ecological productivity of world average land of a specific land-use type (like cropland) and the average productivity of all biologically productive lands on Earth.

In the absence of such data, currently Global Footprint Network’s National Footprint Accounts define equivalence factors as the ratio of the maximum agricultural potential of land of a specific land-use type (like cropland) and the average productivity of all biologically productive lands on Earth. To this effect, the accounts use the suitability indexes from FAO's Global Agro-Ecological Zones (GAEZ) assessment combined with information about actual areas of cropland, forest and grazing area from FAOSTAT, a UN database provided by FAO (FAOSTAT; FAO and IIASA, 2000). The GAEZ model divides all land globally into five categories, each of which is assigned a suitability score:

Very Suitable – 0.9

Suitable – 0.7

Moderately Suitable – 0.5

Marginally Suitable – 0.3

Not Suitable – 0.1

The current equivalence factor calculation assumes that the most productive land is put to its economically most productive use. The calculations assume that the most suitable land available will be planted to cropland, the next most suitable land will be under forest, and the least suitable land will be grazing area. The equivalence factor is calculated as the ratio of the average suitability index for a given land type divided by the average suitability index for all land types. This means that current (and future) equivalence factors are based on global-average agricultural suitability of various biomes.

Still, Global Footprint Network also agrees with Eurostat's perspective (Schaefer et al., 2006) that the equivalence factors need to be strengthened, since they are at the core of Ecological Footprint accounting. Ideally, equivalence factors would be based on spatially explicit measures of potential net primary productivity. Globally consistent and reliable data sets on potential net primary productivity do not yet exist. However, approximations are needed to improve on the current even more basic estimates of equivalence factors.

Better equivalence factors could help bridge the current gap between theory and practice of measuring global hectares. In ideal theory, a global hectare is independent of the chosen land use. However, in practical application this is not fully realized. Still, if a piece of forest is converted into cropland, it is incorrect to assume that biocapacity automatically goes up. While the equivalence factor goes up (cropland hectares represent typically higher biocapacity than forest hectares), the yield factor may drop. The latter factor drops because relatively high-yielding forest may be converted into relatively low-yielding cropland. But there is still a research and method development gap in that changes in land use in current accounts would most likely shift the resulting biocapacity estimate.

To isolate the portion of yield change that is human-induced, and to present it as a separate factor, National Footprint Accounts also employ an 'intertemporal yield factor' (Borucke et al., 2013). It captures the change of productivity over time. This factor enables us to more meaningfully depict time series. With the help of this factor, the measurement unit of global hectares can be mapped against 'constant global hectares'. This constant-global-hectares logic is similar to dollar measurements being expressed in constant (in this case 'inflation adjusted') dollars. These constant global hectares represent a set portfolio amount of products and services that an average hectare was able to provide in a given year. In this way, a given level of consumption (and production) can more meaningfully be compared across years. When expressing National Footprint Account results, Global Footprint Network calls the units 'global hectares' rather than 'constant global hectares' to keep communication simple.

Do Ecological Footprints provide a pollution measure?

The Ecological Footprint attempts to measure demand on biocapacity. It does not include aspects outside of that scope. For instance, pollution affecting human health is not captured in the Footprint; nor are environmental aspects such as noise, urban air pollution, or radioactivity which have an unclear or undocumented biocapacity dimension(Kitzes et al., 2009). However, pollution that affects biological productivity (or bioproductivity) should be included. The limitation is that the demand of those kinds of pollution on biocapacity is not systematically tracked, therefore there are no globally comparable data sets to include those impacts in Ecological Footprint accounts. Examples of such pollution are acidification or eutrophication (some local Footprint studies have, however, included such pollution impacts) (Wackernagel et al., 1999).

Note, however, that as these pollution effects change biocapacity, this change will be recorded by future biocapacity accounts. But ideally, in more perfect accounts, this change in biocapacity should be debited against the present Footprint. This omission indicates the general bias of Footprint accounts: the high likelihood that they exaggerate biocapacity and underestimate Footprints.

Is the Ecological Footprint biased against international trade?

Some critics have argued that Ecological Footprints are biased against international trade (van den Bergh and Verbruggen, 1999; Grazi et al., 2007; Stiglitz et al., 2009). The Ecological Footprint does not bias against trade, but instead simply reports the world as it currently stands.

It documents that many countries are running biocapacity deficits and may therefore depend upon biocapacity from external sources or on local overuse. Some of this dependence may be covered in the form of net-imports. Just as money can be used to describe trade flows, so can Footprint accounting describe these flows in terms of embodied biocapacity. The Ecological Footprint approach is parallel to that of the many studies dealing with carbon (for example, Davis et al., 2011; Hertwich and Peters, 2009; Peters and Hertwich, 2006; Peters et al., 2011) or water (Hoekstra and Chapagain, 2007) embedded in international trade. The Ecological Footprint simply expands the analysis to assess a broader range of ecological resources and services embedded in internationally traded products. While it is true that some users of Ecological Footprint results have made anti-trade claims (Willey and Ferguson, 1999), the Footprint method as such offers no prescriptions about trade regimes.[8] Rather it helps to show that resources within the world are limited and to recognize that if all nations run at a biocapacity deficit then this will inevitably lead to a global depletion of the planet's ecological assets.

Is the carbon portion of the Footprint exaggerated?

Some critics have questioned the rationale behind the carbon portion of the Footprint (Ayres, 2000; IMV, 2002; Neumayer, 2013). The Ecological Footprint builds on the premise of capital maintenance. Its accounts answer the question of how much biocapacity is needed to provide all the services demanded by people. If people demand more services than are being regenerated ('overshoot') then the accounts calculate how much more biocapacity is needed to cover this demand. In the case of the carbon Footprint, the accounts calculate how much biocapacity is needed in order to not increase the carbon concentration in the atmosphere in that year (that is, not leaving a debt for future years). If carbon is absorbed through human means or technological intervention, then it is not counted. The accounts only include the carbon that humanity leaves for the biosphere to take care of. Given humanity's significant dependence on fossil fuels, it is not surprising that the carbon Footprint component currently makes up such a large proportion of the Ecological Footprint (60% globally in 2016). But a century ago, and for most lower-income countries, the carbon Ecological Footprint is quite small (see Galli, Kitzes et al., 2012). Moreover, if humanity complies with the Paris goal, humanity's carbon Footprint should be (close to) zero by 2050.

Hence, the dominance of carbon within the overall Ecological Footprint is by no means exaggerated, but simply represents the real amount of carbon dioxide that is emitted most prolifically through the burning of fossil fuels. To strengthen the case, Global Footprint Network recalculated the average sequestration capacity of forests using the newest available data sets. And as mentioned above, the conclusion was a 25% smaller sequestration rate per global hectare than previously calculated (Mancini et al., 2016).

Over the last few years there has been a tendency to focus on carbon emissions, but this is not the only problem. The Ecological Footprint captures many more issues than the emission of carbon dioxide. For instance, it makes the connection between emissions and land-use aspects, a link also acknowledged in the Paris Climate Agreement of 2015. Further, since the Footprint accounts track availability of and demand on natural resources from different land types, this information is useful for understanding the availability of space for biodiversity. Again, the accounts do not prescribe how much of the biocapacity should be left for wild species. Obviously the amount of biocapacity left for biodiversity shapes biodiversity outcomes, together with other factors such as invasive species, toxicity, fragmentation and management. Also, the Footprint accounts for the forestry land that is cut down and converted to cropland and therefore implies a loss of biodiversity and ecosystem services.

If indeed humanity should decide to move aggressively out of fossil fuels, Footprint accounting helps to identify to what extent this move leads to a burden shift to other land types (for example, cropland for biofuels or fuel wood), or truly reduces humanity's demand on biocapacity. Lack of biocapacity also indicates risk, should it become necessary to move out of fossil fuels and require more biomass as energy source. Also, less availability of cheap fossil fuels may have a significant impact on agricultural productivity, potentially increasing the land demand for agriculture. All these effects are captured by Footprint accounting.

What about nuclear energy?

While in earlier Footprint accounts (up to 2007) nuclear energy was included, assuming that the Footprint of nuclear electricity would be at par with that of coal-powered electricity (in order to avoid the debate whether coal or nuclear is better), accounts since the 2008 National Footprint Accounts Edition no longer include nuclear apart from the CO_2 emitted through construction and use of the plants. But it is also emphasized that Ecological Footprint methodology is not the most relevant framework for assessing the risks and benefits of nuclear energy. More significant are questions of costs, operational risks, long-term waste storage and the potential for nuclear proliferation.

Still, Footprint assessments can reveal certain impacts. For instance, a more recent study, published by WWF Japan, showed the biocapacity impacts from the Fukushima nuclear accident in 2011. The exclusion zone, or 'warning zone' as it is officially called, with a 20 km radius, represents 2.7% of Japan's biocapacity. The report does not provide information on how long the exclusion zone may be unsafe for human use. But if this zone is not inhabitable or usable by people for 1000 years, it would imply that this one accident occupied 27-fold Japan's biocapacity of that year. Also, the report documents that the area currently contaminated to a level that is higher than pre-accident legal limits is about 10% of Japan's biocapacity (WWF Japan and Global Footprint Network, 2012).

How do Ecological Footprint accounts relate to planetary boundaries?

Planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) identify key physical quantitative conditions that are needed to maintain the integrity of the biosphere. Nine areas have been identified, in which transgressions could lead to shifts in the integrity, potentially irreversibly moving the biosphere out of the stable conditions which characterized the Holocene.

Therefore, one could interpret the planetary boundaries as well as the inverse of the ingredients for healthy, productive ecosystems that can maintain their integrity. In other words, staying within the safe operating zone with each of the nine ingredients enables the productivity of the biosphere, which Ecological Footprint accounting calls the biosphere's 'biocapacity'. These boundaries translate into the specific ingredients that could be called 'the production factors' to enable biocapacity:

- Stable climate
- Healthy biodiversity
- Sufficient nutrients

- Protective ozone layer
- Absence of pollutants
- Clean and sufficient fresh water
- Absence of acidification in both water and soils

The Ecological Footprint does not quantify, in contrast to the planetary boundaries, trigger points that lead to irreversible change. Rather, it tracks human demand against biological regeneration. If demand exceeds regeneration, the resulting natural capital loss or degradation will eventually become a trigger point since one cannot indefinitely take more from ecosystems than they can renew. It summarizes the overall outcome of transgressing planetary boundaries and quantifies this transgression in one 'biocapacity' number representing the regenerative capacity of the biosphere.

There is strong complementarity between planetary boundaries and Ecological Footprint. Ecological Footprint is less complex, and not a broad field of academic inquiry, but rather a biophysical accounting approach focused on a key output of the biosphere: biocapacity. Ecological Footprint is basic, using the fundamental thermodynamic laws and biological principles (such as competition for space to feed organisms, differences in NPP of various ecosystem configurations) enabling this biocapacity accounting by adding up all the mutually exclusive spaces people use to provide for people's demands (their Footprint), which then can be compared with the productive spaces available (biocapacity). The planetary boundaries concept is more granular on the biocapacity side, documenting the key parameters that enable stable, productive biocapacity around the globe.

5. Research arguments that strengthen Ecological Footprint accounting and its development

As originators of the method and stewards of the most widely used Ecological Footprints accounts in use today, Global Footprint Network (www.footprintnetwork.org) is the first to acknowledge that the Footprint accounts can and must be improved. Global Footprint Network considers the current National Footprint Accounts as evidence that biocapacity accounting is possible, with far more potential for accuracy and detail. As a scientific organization aiming to implement policy-relevant tools and analyses, Global Footprint Network asks others to test and review the results, and depends on input and suggestions from others regarding calculation methods and potential improvements.

Global Footprint Network scientific testing goes a long distance beyond academic peer reviews. It proactively seeks the review of the ultimate users of Footprint accounts – national governments. The main reason is that nations are the ultimate risk bearer of biocapacity deficits, and their governments need to have access to results they have confidence in.

To build this confidence, Global Footprint Network's comprehensive review efforts start with transparency: the method is published on the Network's website and in academic journals. Of course, it also engages in academic peer reviews – but peer review is just one element, because such reviews do not go deep enough, and the academic community does not depend on the reliability of results in the same way that national governments do. In addition, therefore, Global Footprint Network directly invites national governments (and their respective agencies) to verify the assessments – including suggesting improvements. About 12 such assessments have been completed and some of them are listed on Global Footprint Network's website at www.footprintnetwork.org/reviews. Completed assessments include that from the European Parliament (ECOTEC, 2001), Switzerland (von Stokar et al., 2006; Frischknecht et al., 2016), Luxembourg (Hild et al., 2010), United Arab Emirates (Abdullatif and Alam, 2011; Galli, Martindill et al., 2016), European Commission (Best et al., 2008), Japan (see for details WWF Japan and Global Footprint Network, 2012, p. 49), or the UK (RPA, 2007). An interesting example of a government review is that of the French SOeS institute (SOeS, 2010), which independently reproduced the French Footprint time trends within 1 to 3% of Global Footprint Network's results, using their own data and the method described on Global Footprint Network's website.

In the academic and the public policy literature, there are numerous valid criticisms that challenge the Ecological Footprint method or its results, many of which form the basis for an active research agenda, a good summary of which is provided by Kitzes et al. (2009).

In general, there are two types of criticisms: *fundamental* (is this a valid approach?) versus *incremental* (how can the approach be improved?). Fundamental criticism is essential and to be valid of any research, it needs to follow a logical sequence, with each step building on the one before (see Box 33.1). The sequence starts with testing whether the research is based on an empirically testable research question. If it is, then critics should probe the relevance of the research question to make sure it provides information that is relevant to public policy. Step 3 involves assessing whether a better method exists elsewhere to answer the research question (and if not, then reviewers can suggest possible ways to make the examined method stronger). Finally, if an examined study passes these three steps, critics can still reject it if they can show that society would be better off without the study's results. This may be the case if the proposed answers are deemed to be more misleading than informing.

Box 33.1 Logical sequence for reviewing and criticizing research 1 Does it build on a clearly defined, testable research question? 2 If yes, is the research question relevant to the intended audiences? 3 If yes, are there more accurate methods available elsewhere for answering this particular research question? 4 If not, is society better off without the results this method generates?

Much criticism against the Ecological Footprint criticism arises from the reviewers' apparent confusion about what the research question behind Footprint accounting actually is. Because Footprint accounting takes a systems view, people often assume it covers issues that it is not designed to measure. Examples of such Footprint criticism are found in arguments made by van den Bergh and Verbruggen (1999), Grazi et al. (2007), van Kooten and Bulte (2000), Fiala (2008), Grazi and van den Bergh (2012), Giampietro and Saltelli (2014) or Blomqvist et al. (2013). None of these studies include step 1 and 2 of this logical sequence in their argumentation. As a result, many of these studies are irrelevant to the Footprint's research question. Following steps 1 and 2 would avoid such fallacies. The actual premises and scope for the Footprint accounting are outlined in the research questions addressed in the previous section.

Others question the validity of the Footprint for conclusions they make themselves, rather than addressing the four steps outlined in Box 33.1. As a consequence, they present immaterial conclusions. Examples are given in Box 33.2 and also include the Stiglitz Report (Stiglitz et al.,

2009) or van den Bergh and Verbruggen (1999), which refute Footprint accounts for being anti-trade when in reality the Footprint accounts are not.

Box 33.2 'The Footprint is not perfect; therefore, we should not use it'.

Some government agencies have used scientific reviews in order to legitimize their unwillingness to adopt Footprint accounting in their own practice. The argument boils down to the statement: 'Footprint results are not perfect; therefore, they should not be used'. An example of such an approach is RPA (2006) and RPA (2007), two consecutive studies commissioned by DEFRA, the UK's ministry of environment. Mathematically speaking, such a statement is true for any research, because by definition, scientific inquiry is never perfect, but a continuous process of learning and improving. While rhetorically, such an argument generates the perception that diligent scientific analysis showed that the Footprint is unfit for use by the agency, the scientifically relevant and honest question to answer should have been: why would the agency be better off not having the analysis? (step 4). Therefore, we include the plea in this chapter to make sure criticism is driven by an honest scientific inquiry (as outlined in Box 33.3) rather than by rhetorical convenience. Obviously, this is true for any research, particularly research critical for public welfare.

In the same vein, few studies on fundamental Footprint criticisms explicitly discuss whether the Footprint question is relevant or not (a notable exception is Schaefer et al., 2006). Discussing the relevance of the research (step 2 of Box 33.1) should be a prerequisite for any fundamental criticism. Global Footprint Network's position is that the Footprint research question is central to sustainability. It holds that sustainability cannot be meaningful unless the availability or regenerative capacities of the ecological constraints of nature, within whose boundaries sustainable development must act, are known. Just as it is important for farmers to know the size of their farm, whether their farmland extends over 5000, 500 or 5 hectares, as having this knowledge about the capacity of the land makes a significant difference to the opportunities that are available to the farmer, one could contend that the same logic applies to a region or even the whole world. By understanding the restrictions of the planet's capacity and where the limitations lie, humanity can move towards sustainability in an informed manner.

Incremental criticism addresses the question: *How can the method be improved?* Most published criticism is of this incremental nature – and this is the area on which Global Footprint Network's current development of the methodology is also focused. For example, Global Footprint Network is working on making the trade assessments of the National Footprint Accounts compatible with the newest insights and analysis from Multi-Regional Input-Output (MRIO) models. But there is still significant work to be done to harmonize the approaches (Ewing et al., 2012; Galli, Weinzettel et al., 2012). Global Footprint Network is currently focusing on an MRIO-assessment based on the newest Global Trade Analysis Project (GTAP) database from Purdue University, GTAP9 (Aguiar et al., 2016). This provides a parallel methodology for analyzing resource flows, in addition to the classical National Footprint Accounts trade analysis based on product flows documented by the United Nations' COMTRADE database that tracks trade flows based on customs statistics of imports and exports. Other MRIO assessments are also emerging, such as the EXIOPOL model (Tukker et al., 2009) and the EORA model (Lenzen et al., 2012; Moran et al., 2013, 2017).

One challenge is that MRIO models do not offer the same level of detail of temporal, categorical or spatial coverage as the National Footprint Accounts. (GTAP9, upon which the Footprint based MRIO builds, covers the years 2004, 2007 and 2011, and divides the world into

140 nations, territories and regions, using only 57 categories; in contrast, current National Footprint Accounts include data for 1961–2012 for approximately 240 countries, of which around 150 are published).

One key application of MRIOs is that they allow the overall consumption Footprints to be broken up into activity fields. We call this breakdown the "Consumption Land-Use Matrix" or CLUM for short. The robustness of these assessments can be compared by comparing various years of results against each other, and comparing the distribution of consumption among countries with similar consumption profile. These CLUMs have a number of applications, including opening the possibility to downscale Ecological Footprint results to subnational applications using relative consumption statistics describing the difference between the national demand and that of the analyzed subnational population, whether it is a city, a region or a socio-economic group (Wackernagel, 1998).

Given the significant noise in the trade data sets, MRIO analysis compared over various years, and contrasting them over various years of NFA-based trade assessments, provides insight into ways how to separate data noise from data signal, an aspect current MRIO analysis is still weak on.

Harmonizing National Footprint Accounts with the emerging MRIO models, together with the aforementioned search for understanding the 'fragility of biocapacity', represent the most significant research frontiers in the Footprint accounting science, opening significant analytical possibilities such as the possibility of tracking trade flows more consistently as well as to the country of origin. Further, it allows researchers to break overall demand into final demand categories.

6. Conclusions

Ecological Footprint accounting is an answer to just one basic question emerging from the need to make our societies and economies operate within the means of our planet. It attempts to quantify the 'scale question' that is at the core of the Ecological Economics discipline (Daly, 1977; Daly and Farley, 2004). While there is still much room for improvement, a number of independent reviews by government agencies – as mentioned above – have confirmed the validity of the assessment.

Criticism is needed for improving the accounts so they can better answer the underlying research question. Much criticism is valid and is being addressed in the research agenda of the Footprint community. But there is also much criticism based on misconceptions about what Footprint accounting really is. Hopefully this contribution helps to clarify the distinction between these two types of criticism.

Notes

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1 This chapter builds on Mathis Wackernagel, Gemma Cranston, Juan Carlos Morales, Alessandro Galli, (2014). “Chapter 24: Ecological Footprint Accounts: From Research Question to Application”, in Giles Atkinson, Simon Dietz, Eric Neumayer and Matthew Agarwala (eds), 2014, *Handbook of Sustainable Development*: second revised edition. Edward Elgar Publishing, Cheltenham, UK ISBN-13: 978–1782544692

2 A comprehensive review of Ecological Footprint applications is provided by Andrea Collins and Andrew Flynn (2015).

3 This approach was originally developed as part of Aurélien Boutaud’s PhD dissertation (2002a). His approach was developed further in a collaboration between Boutaud and Global Footprint Network (Moran et al., 2008; Global Footprint Network, 2009).

4 Note that the comparison with global average biocapacity mainly provides a global overview. This then can be taken a step further, comparing with local biocapacity. For many countries, local availability of biocapacity (and financial means to access biocapacity

from elsewhere) are a more significant determinant of resource access than the global average.

5 The promotion and slight distortion of the carbon Footprint by BP was, in the eyes of Global Footprint Network, a lucky occurrence. Global Footprint Network had been concerned about the possibility that a large organization like BP could significantly distort and confuse the concept. But in this case, it has, in spite of the slight distortion from the original concept, helped to promote rather than thwart the understanding that there are global limits, and that consumption is an ultimate driver of resource demand (Fill and Hughes, 2008, p. 156; Safire, 2008).

6 In their 2009 Climate Change Adaptation Report, they state:

> The report's point of departure is that we are unlikely to be far more successful at curbing our CO_2 emissions in the near future than we have been over the past decade or so. And even with vigorous mitigation effort, we will continue to use fossil fuel reserves until they are exhausted. However, by then, atmospheric CO_2 levels may have risen to about 1700ppmv compared to an average of 383ppmv today.

(www.imeche.org/Libraries/Key_Themes/ClimateChangeAdaptationReportIMechE.sflb.ashx)

8 Humanity has maintained use of resources outside the realms of settlements since the beginning of civilization. Indeed, most current communities are far from self-sustaining, and exist by drawing upon the resources beyond their borders. Even hunter-gatherer tribes depended on far larger areas than the settlements themselves. Thus the space required to sustain populations has historically been far larger than the main living space of communities. A footprint application in this context, commissioned for a Canadian court case, is explained on Global Footprint Network's webiste at https://www.footprintnetwork.org/2014/07/18/canada-ecological-footprint-instrumental-supreme-courts-ruling/ (accessed March 22, 2018).