Environmental footprints: assessing anthropogenic effects on the planet's environment

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Chapter 5

Understanding the complementary linkages between environmental footprints and planetary boundaries

Reprint with minor changes from:

Fang, K., Heijungs, R., De Snoo, R. G., 2015. Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–boundary environmental sustainability assessment framework. Ecological Economics 114, 218–226. DOI: 10.1016/j.ecolecon.2015.04.008.

Abstract

While in recent years both environmental footprints and planetary boundaries have gained tremendous popularity throughout the ecological and environmental sciences, their relationship remains largely unexplored. By investigating the roots and developments of environmental footprints and planetary boundaries, this chapter challenges the isolation of the two research fields and provides novel insights into the complementary use of them. Our analysis demonstrates that knowledge of planetary boundaries improves the policy relevance of environmental footprints by providing a set of consensus-based estimates of the regenerative and absorptive capacity at the global scale and, in reverse, that the planetary boundaries framework (PBF) benefits from well-grounded footprint models which allow for more accurate and reliable estimates of human pressure or impact on the planet's environment. A framework for integration of environmental footprints and planetary boundaries is thus proposed. The so-called footprint–boundary environmental sustainability assessment (F–B ESA) framework lays the foundation for evolving environmental impact assessment to environmental sustainability assessment aimed at measuring the sustainability gap between current magnitudes of human activities and associated capacity thresholds. As a first attempt to take advantage of environmental footprints and planetary boundaries in a complementary way, there remain many gaps in our knowledge. We have therefore formulated a research agenda for further scientific discussions, mainly including the development of measurable boundaries in relation to footprints at multiple scales and their trade-offs, and the harmonization of the footprint and boundary metrics in terms of environmental coverage and methodological choices. All these points raised, in our view, will play an important role in setting practical and tangible policy targets for adaptation and mitigation of worldwide environmental unsustainability.

5.1. Introduction

A central challenge for sustainability is how to meet human needs while preserving our planet as a pleasant place for living and as a source of welfare (Kates et al., 2001; Kratena, 2004). A necessary, though not sufficient, step in achieving this goal is the identification and measurement of carrying capacity—the maximum persistently supportable load that the environment can offer without impairing the functional integrity of ecosystems (Catton, 1986; Rees, 1996). Attempts have been made to define human carrying capacity, from a demographic perspective, as the maximum human population which can be raised by the Earth in a way that would ensure the interests of future generations (Daily and Ehrlich, 1992; Ehrlich, 1982). This definition is, however, seemingly somewhat pedantic and meaningless, because the growth in global population remains virtually unchanged and of course cannot be diminished by force even though Ehrlich (1982) already warned of the overshoot of human carrying capacity.

In response to the then-current debates surrounding carrying capacity, the ecological footprint was conceived to represent the spatial appropriation ideally required to support a given population (Rees, 1992; Wackernagel and Rees, 1996). It can be regarded as a complement to carrying capacity. Leaving out many key aspects of sustainability by design (Goldfinger et al., 2014), the ecological footprint practically equates human demand for nature with that for biotic resource provision and energy-related carbon sequestration. Subsequently, an array of footprint-style indicators has been spawned as complements to the communication of pressure or impact that humanity places on the planet's environment. This array includes the water footprint (Hoekstra and Hung, 2002), chemical footprint (Guttikunda et al., 2005), carbon footprint (Wiedmann and Minx, 2008), phosphorus footprint (Wang et al., 2011), nitrogen footprint (Leach et al., 2012), biodiversity footprint (Lenzen et al., 2012), material footprint (Wiedmann et al., 2015), and so on.

At the same time, revisiting sustainability limits has never stopped since the publication of Limits to Growth (Meadows et al., 1972), a remarkable book which for the first time alarmed the public with environmental constraints on population expansion. In 2009, as conceptually similar to carrying capacity, a framework of planetary boundaries was launched by Rockström et al. (2009a, 2009b). By its definition, capacity thresholds for a broad range of environmental issues at the global scale are explicitly identified, including climate change, rate of biodiversity loss, interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, chemical pollution, and atmospheric aerosol loading. Because of the initiative of providing quantitative and measurable preconditions for human development, the planetary boundaries concept has grown in interest over recent years, with particular focus on its implications for Earth system governance (Biermann, 2012), biospheric monitoring and forecasting (Barnosky et al., 2012), green economy (Kosoy et al., 2012), food security (De Vries et al., 2013), and environmental equity (Steffen and Stafford Smith, 2013).

There have been a considerable number of studies that deal with either environmental footprints or planetary boundaries, and only very few that discuss both topics within one study. Moreover, the chapters that address environmental footprints together with planetary boundaries employ different principles, frameworks, and terminologies. This chapter aims to highlight the promise of connecting environmental footprints and planetary boundaries by exploring their relationships and synergies, by providing a harmonized framework and terminology, and by offering novel insights into their complementary use.

To that end, the remainder of this chapter is structured as follows: Section 5.2 provides evidence on the importance of the planetary boundaries concept for making environmental footprints policy-relevant; Section 5.3, on the contrary, investigates the role of environmental footprints in improving the scientific robustness of the planetary boundaries framework (PBF); Section 5.4 demonstrates the benefits of jointly defining environmental sustainability; Section 5.5 proceeds with a detailed discussion of the challenges of synthesizing the footprint and boundary metrics and how these inform a research agenda.

5.2. Why knowledge of planetary boundaries is important for making environmental footprints policy-relevant?

Many environmental footprints have proven useful in measuring the pressure or impact exerted by human activities (Galli et al., 2012; Leach et al., 2012). Meanwhile, it has been widely acknowledged that focusing exclusively on a single footprint runs the risk of shifting the environmental burden to other impact categories (Fang et al., 2014). Shrinking the product carbon footprint, for instance, could induce a remarkable increase in other environmental footprints (Laurent et al., 2012). Likewise, reductions in water footprint by inter-basin water or food transfer are found at the expense of increasing energy footprint (Gerbens-Leenes et al., 2009). Considerable evidence from the literature calls for a policy transformation from assessing single footprints in isolation to tackling diverse footprints, i.e., a footprint family (Fang et al., 2014; Galli et al., 2012), from an integrated perspective.

However, this is not enough. Man should not merely minimize his environmental footprints, which many footprint users concentrate on, but make sure these footprints stay within the planetary boundaries, which is a critical prerequisite for sustainable development (Fang and Heijungs, 2015; Heijungs et al., 2014). As pointed out by Lancker and Nijkamp (2000), an indicator does not provide any information on sustainability unless a reference value is given to it. A simultaneous assessment of environmental footprints and related capacity thresholds is therefore of vital importance, representing the evolution of backtracking towards a prognostic and preventive measure that helps prevent human activities from triggering undesirable environmental changes.

The ecological footprint was designed in such a way that it can be readily compared to available bio-productive area of the Earth, which is referred to as "biocapacity" (Rees, 1992; Wackernagel and Rees, 1997). The difference between the ecological footprint and biocapacity reflects a form of sustainability gap, explaining why our world is operating in a state of overshoot with respect to biotic resource extractions and energy-related carbon emissions (Niccolucci et al., 2009; Wackernagel and Rees, 1997). The inclusion of biocapacity is unique and important, making the ecological footprint outstand from many other footprint indicators (Ewing et al., 2012; Hoekstra, 2009).

In a similar case to that of the ecological footprint, the blue and gray water footprints were envisaged as a way of comparing with the blue and gray water boundaries, respectively, where the results are expressed in the form of a quotient (Hoekstra et al., 2012; Liu et al., 2012). The footprint-to-boundary ratios depict the relative severity of water scarcity and pollution as a consequence of the mismatch between water withdrawal and renewable supply. The ecological and water footprints are, in this sense, able to inform policy makers on to which degree the biophysical limits of the biosphere and hydrosphere are being approached or exceeded, respectively (Costanza, 2000; Galli et al., 2012).

Table 5.1 summarizes existing practices that aims at incorporating the boundary concept into footprint analysis. As seen, so far not all of the footprints include a comparison to quantified capacity thresholds. In fact, many do not, although this is being perceived as increasingly useful. Even for those which have been linked to a threshold value already, there remain limitations that have been a notable source of controversy in footprint analysis; thus, we believe that recent developments regarding planetary boundaries will inspire and facilitate the ongoing process of benchmarking environment footprints against capacity thresholds.

Table 5.1. Summary of existing practices for relating environmental footprints to planetary boundaries.

Footprint category	Key elements of relating a footprint to a boundary	Advantages over the sole use of the footprint	Limitations
Blue water footprint (Hoekstra et al., 2012)	• Blue water footprint: a measure of the volume of surface and groundwater consumed and then evaporated or incorporated into a product, sector, or the whole economy. • Blue water availability: a measure of the total natural runoff minus presumed flow requirements for ecological health. • Blue water scarcity: equal to dividing blue water footprint by blue water availability.	By screening the monthly water scarcity in 405 major river basins throughout the world in 1996-2005, a large number of people living under sever water stress. The world-average ratio of blue water footprint to blue water availability is found to be about 94%, which suggests that the globe has experienced a low water scarcity.	The accounting of blue water availability does not properly deal with the perturbation of seasonal runoff patterns by dams' flow regulation, and similarly for the blue water footprint that does not include evaporation from artificial reservoirs. The water scarcity indicator without regard to green water component is incomplete.
Carbon footprint (Hoekstra and Wiedmann, 2014)	• Carbon footprint: a measure of the total amount of greenhouse gas emissions that are directly and indirectly caused by an activity or are accumulated over the life cycle of a product. • Carbon boundary: a measure of the maximum sustainable carbon footprint level at the global scale. • Carbon deficit: equal to subtracting carbon boundary from carbon footprint.	The carbon footprint has been put in the context of a planetary carbon boundary, which is estimated to be 18-25 Gt CO_2-eq./yr. It means that the global carbon footprint should be reduced by 60% in 2010-2050 in order to achieve the global warming target of maximum 2 ℃.	There is not yet a consensus on the most appropriate way of allocating the responsibility for carbon reduction to national and sub-national scales, i.e., a fair share for different stakeholders given their historical performance, capacity and other considerations is lacking.
Chemical	• Chemical footprint: a measure of the	In addition to computing chemical footprint, two	The methodology proposed faces the challenges of

footprint (Zijp et al, 2014)	expected cumulative impacts of chemical mixtures on aquatic ecosystems for a region. • Chemical boundary: a measure of the sustainability level or policy target expressing which chemical impact is acceptable. • Chemical pollution index: equal to dividing chemical footprint by chemical boundary.	approaches to define a chemical boundary are introduced from the realms of chemical management practice (policy boundary) and of research into ecosystem vulnerability (natural boundary), so that one can account for the water volume needed to dilute chemical pollution due to human activities to a level below a specified boundary condition.	finding ways to reduce the uncertainty of weighting that aggregates the impacts on different scales and compartments, and of the complex natural systems that would hamper the distribution of spatially variable and ecosystem specific chemical boundaries. The resulting chemical footprint is hypothetical and thus, comparing the footprint with the boundary should be conducted with care.
Ecological footprint (Borucke et al., 2013)	• Ecological footprint: a measure of the land and water area required to support a given population with biotic resource extractions and energy-related carbon emissions. • Biocapacity: a measure of the biosphere's regenerative capacity in terms of the Earth's terrestrial and aquatic surface that is biologically productive to provide the basic ecosystem services—food, fiber and timber products that humanity consumes. • Ecological deficit/surplus: a measure of the overshoot/reserve of biocapacity relative to its ecological footprint.	The comparison to biocapacity supports the existence of global overshoot which first occurred in the mid-1970s. In 2008, mankind's ecological footprint exceeded at least 50% of the biocapacity, consuming ecosystem services that require about 1.5 planets to regenerate and to assimilate.	The carbon component in many cases contributes almost 100% or even more of the ecological deficit due to the omission of the absorptive capacity in current ecological footprint accounting. Present global overshoot would be replaced by a surplus of 0.6 planets without considering the carbon component.
Gray water footprint (Liu	• Gray water footprint: a measure of the volume of freshwater required to	The calculated water pollution levels of different river basins show a large variation among	The water pollution level of a basin below 1 does not necessarily reflect an avoidance of

et al., 2012)	assimilate the loading of pollutants given natural background concentrations and existing ambient water quality standards. • Pollution assimilation capacity: a measure of the environmental water needs by subtracting the presumed flow requirement for ecological health from the total runoff. • Water pollution level: equal to dividing gray water footprint by pollution assimilative capacity.	different periods, generally increasing in 1970-2000. In 2000, about two-thirds of the basins have their pollution assimilative capacity fully consumed for anthropogenic nitrogen or phosphorus.	eutrophication at the sub-basin level. Defining the overall water pollution level as the largest calculated one among all different nutrient forms of nitrogen or phosphorus is questionable, as this may overly simplify the cumulative effects of multiple aquatic pollutants.

5.3. Why environmental footprints are important for making the PBF scientifically robust?

Contrary to popular belief, Rockström et al.'s framework is not only about planetary boundaries, but also about current state estimates—a neglected field of research into the planetary boundary issues. In other words, its ultimate goal is not to quantify a boundary, but to quantify the transgression or reserve of a boundary, determined by the comparison of planetary boundaries and current human pressure. As a whole, Rockström et al.'s estimates are reliant on literature review reflecting expert knowledge that inevitably contains uncertainty, subjectivity and arbitrariness (De Vries et al., 2013; Lewis, 2012). Nevertheless, currently this is perhaps the best way to quantify planetary boundaries in view of the difficulties of prediction. Furthermore, by using the best available knowledge and the precautionary principle, planetary boundaries are claimed to be more science-based than a common policy framework (Nykvist et al., 2013).

However, the problem is that Rockström et al. do so to measure the current status of investigated environmental issues, which could have been more rigorous and robust if appropriate environmental models are used instead. As environmental footprints are derived from a great number of quantitative models, of which the majority have a broad base of acceptance with respect to documentation, transparency and reproducibility (Fang et al., 2014; Hoekstra and Wiedmann, 2014), it is natural to expect that the methodological maturity of footprints would be able to enhance the expression and quantification of current estimates involved in the PBF.

We illustrate this with two brief examples. On the climate change, for instance, atmospheric concentration of carbon dioxide (CO_2) and radiative forcing have been chosen as two control variables for setting climate boundary, but also for measuring current climate state (Rockström et al., 2009a). The concurrent use of the two variables represents an unnecessary dual-objective trade-off and thus may compromise the usefulness of setting carbon boundary. By using carbon footprint—a consensus impact indicator of climate change (Hellweg and I Canals, 2014; Minx et al., 2013), a convergence of these two independent variables is harmoniously achieved. According to Hoekstra and Wiedmann (2014), global carbon footprint is amounted to 46-55 Gt CO_2-eq./yr for 2011.

In the case of freshwater use, Rockström et al. pose that at present the annual global water consumption is approximately 2600 Gm^3/yr. Apart from the uncertainty of this approximation, the value only accounts for the evaporation and transpiration from surface and ground water—a small fraction of total freshwater usage (Molden, 2009), ignoring green water that is estimated to be 6700 Gm^3/yr (Hoekstra and Mekonnen, 2012). The serious underestimate of human freshwater consumption should have been overcome by aggregating the blue and green water footprints using existing water footprint models with high degrees of scientific certainty.

The two cases as referred to demonstrate the necessity of standardized and reproducible footprint models to support the assessment of actual human-induced environmental pressure or impact. One may extrapolate that the scientific foundation of the PBF will be consolidated by the substitution of well-grounded footprint models for rough current estimates. However, this does not justify the incorporation of capacity thresholds into footprint indicators within the existing footprint discussions. Ambiguity and confusion may occur, as proven by the ecological footprint which sometimes refers to the footprint itself, and at other times refers to both the footprint indicator and biocapacity. As a result, the purpose of the remainder of this chapter is not to consider boundaries as a part of footprints, nor to consider footprints as a part of boundaries. Instead, we keep the footprint metric and boundary metric separate, while taking the two as complements in assessing environmental sustainability.

5.4. Complementary use of environmental footprints and planetary boundaries for environmental sustainability assessment

5.4.1. The root of the environmental sustainability concept

Responding to the increasing challenge of finding ways to maintain the carrying capacity of the global ecosystem, the significance of the boundary concept in making sense of environmental sustainability had already been underlined in the late 20th century. For example, Daly (1990) presented an operational principle of sustainable development; that is, the regenerative and absorptive capacity must be treated as natural capital, of which the failure of maintenance leads to unsustainability. Goodland and Daly (1996) legitimized environmental sustainability by three input–output rules: (1) harvest within the regenerative capacity of renewable resources; (2) waste within the absorptive capacity of natural systems; and (3) depletion of non-renewable resources at a rate less than that of renewable substitutes.

Despite the high transparency, completeness and acceptability that Goodland and Daly's definition provides, a fundamental obstacle to environmental sustainability assessment (ESA) is the difficulty in predicting how long a life-supporting system is to be sustainable, rather than in discriminating sustainability and unsustainability after the fact (Costanza and Patten, 1995). This results from a lack of methods for quantifying the regenerative and absorptive capacity. As a breakthrough to fill in this gap, the PBF gives, for the first time, numerical results for capacity thresholds at the global scale. Meanwhile, the footprint metric serves as a counterpart to the boundary metric by offering background values for environmental issues and thereby helping to better understand the concept of environmental sustainability.

5.4.2. A footprint–boundary ESA (F–B ESA) framework

To preserve the planet's environment from facing unexpected or irreversible changes, a first step would be the development of ways of ascertaining whether human activities are kept within permissible limits. Due to their relative emphases and challenges noted above, neither environmental footprints nor planetary boundaries can adequately address this complicated issue solely; therefore, they should rather be used complementarily to make sense of the ESA. In deriving a footprint–boundary representation of environmental sustainability, clarity on definitions of both environmental footprints and planetary boundaries is required. Although there are already many attempts for making the two concepts transparent, we contend that any definitions work satisfactorily only if placed in an appropriate context, i.e., none is able to fit for all purposes. For this reason, environmental footprints and planetary boundaries will be specified as follows:

- **Environmental footprints**: a measure of human pressure or impact on the planet's environment in relation to resource extractions and hazardous emissions. In a mathematical context, we indicate the footprint of pressure i (e.g., carbon emission, water use, land use) as $U_{footprint,i}$.
- **Planetary boundaries**: a measure of the regenerative and absorptive capacity of the Earth's life-supporting systems, beyond which unacceptable environmental changes for humanity may occur. Accordingly we denote the planetary boundary of pressure i as $U_{boundary,i}$.

Mathematically, we do two steps:

- **Step 1** converts an environmental footprint and/or planetary boundary into a common metric. For example, $U_{footprint,CO_2}$, $U_{footprint,CH_4}$, $U_{footprint,N_2O}$ (in Gt/yr) are collectively converted into $Z_{footprint,climate}$ (in Gt CO_2-eq./yr) using the global warming potential (GWP) values. Likewise, $U_{boundary,temperature}$ (in °C) is converted into $Z_{fboundary,climate}$ (in Gt CO_2-eq./yr).
- **Step 2** creates sustainability indicators by looking at: (1) the difference between a footprint and a boundary ($Z_{footprint,i} - Z_{boundary,i}$); or (2) the ratio of a footprint to a boundary ($Z_{footprint,i}/Z_{boundary,i}$).

On the basis of the two steps, a schematic representation of the F–B ESA framework is provided in Figure 5.1. The main function of the F–B ESA framework is to inform policy makers on the distance or ratio between the actual performance and the estimated thresholds, visualizing if the maximum sustainable level has already been breached. By use of the F–B ESA framework, the distinction between environmental sustainability and unsustainability can be explicitly interpreted as follows:

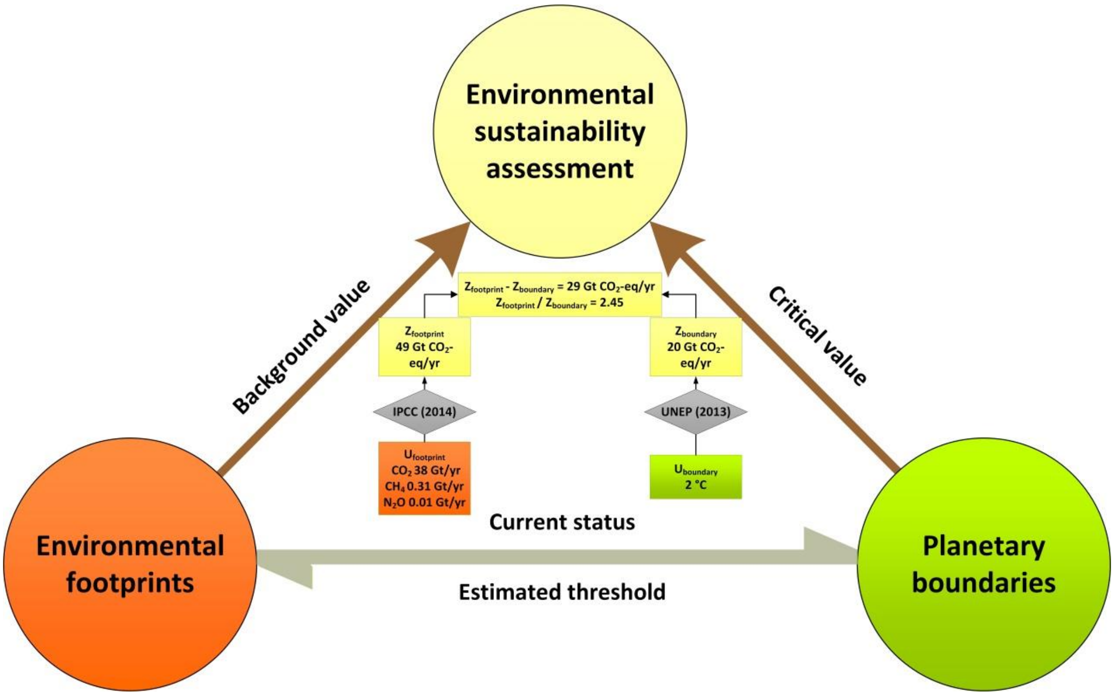

Figure 5.1. The footprint–boundary environmental sustainability framework, along with a procedure for converting and comparing the footprint and boundary metrics, exemplified by measuring the sustainability gap of climate change on the basis of the global carbon budget. While current climate boundary is emerged from the consensus that anthropogenic warming should be limited to below 2 °C (Rogelj et al., 2013), it represents an unnecessary distraction from the "2 °C target" (Allen, 2009). Operational challenges may arise as more than one reduction target should be met simultaneously. For this concern, a proposal for converting the "2 °C target" directly into a mass equivalent metric is given, which is in line with the conversion of three principal greenhouse gases, namely, CO_2, CH_4, and N_2O, to the carbon footprint. IPCC: Intergovernmental Panel on Climate Change; UNEP: United Nations Environment Programme.

- **Environmental sustainability**: the converted footprint of human activities is kept within the relevant converted boundary, ensuring that the planet's environment retains a safe state in which human well-being and prosperity are satisfied ($Z_{footprint,i} - Z_{boundary,i} \leq 0$, or $Z_{footprint,i}/Z_{boundary,i} \leq 1$).
- **Environmental unsustainability**: the converted footprint of human activities already exceeds the relevant converted boundaries, with consequences that would move the planet's environment to an unsafe state in which the stability and resilience of Earth system functioning are being undermined ($Z_{footprint,i} - Z_{boundary,i} > 0$, or $Z_{footprint,i}/Z_{boundary,i} > 1$).

5.4.3. Benefits of the F–B ESA framework

The joint implementation of environmental footprints and planetary boundaries opens the way for a novel and straightforward representation of environmental sustainability. While footprints have been found particularly suited to support decisions in environmental impact assessment (EIA), many of which are limited in visualizing the gaps between what is actually being done and what ought to be done from a sustainability perspective. Examples include the nitrogen, phosphorus and biodiversity footprints. One may argue, for instance, that it is not difficult to imagine the development of nitrogen threshold within the nitrogen footprint framework; this, however, suggests a position that in our view is undesirable because of rejecting the use of existing knowledge on planetary boundaries which has gained considerable interest and support from a broad range of the scientific community.

We believe that ESA represents a step ahead from EIA that is based on descriptive indicators (e.g., environmental footprints) that measure what is happening to the environment (Smeets and Weterings, 1999), as from a consumption-based angle it makes more sense to give consumers the opportunity to take into account their environmental responsibility for closing the sustainability gap. In this regard, a prominent advantage of implementing the F–B ESA framework is that it delivers valuable information on whether or not human activities give rise to a sustainability gap, and to what extent. To meet the public and corporate needs of downscaling planetary boundaries for the allocation of responsibility, developing measurable environmental boundaries at sub-global scales is needed. We classify and exposit the scaling effects of planetary boundaries in depth via Sections 5.5.1 and 5.5.2, together with a discussion of how to harmonize the footprint metric and boundary metric via Section 5.5.3 and of the potential trade-offs of sustainability gaps between various environmental issues via Section 5.5.4.

A further strength of the F–B ESA framework lies in its completeness of capturing key environmental challenges to global sustainability, rather than a single footprint nor a footprint family that covers. As the distinction between a policy target and a natural threshold boundary has been brought to attention (Zijp et al, 2014), there is an ever greater need to understand how the sustainability gap and the policy gap differ. The F–B ESA framework is appropriate for use in distinguishing these two types of gaps. Conceived in simple terms, the sustainability gap is the distance between current status and threshold values anticipated for scientific purposes, though revealed preferences and judgments cannot be completely avoided, and the policy gap is the one between policy targets set with political legitimacy and threshold values. A sustainability gap minus a policy gap represents a measure of implementation gap required to be covered in order to fulfill a commitment that has been enforced by regulation or legislation. A shift from an emphasis on monitoring environmental impacts to an emphasis on measuring sustainability gaps and evaluating the actual effectiveness of policy implementation is therefore realized through the comparison of policy targets and the converted footprints and boundaries (Figure 5.2).

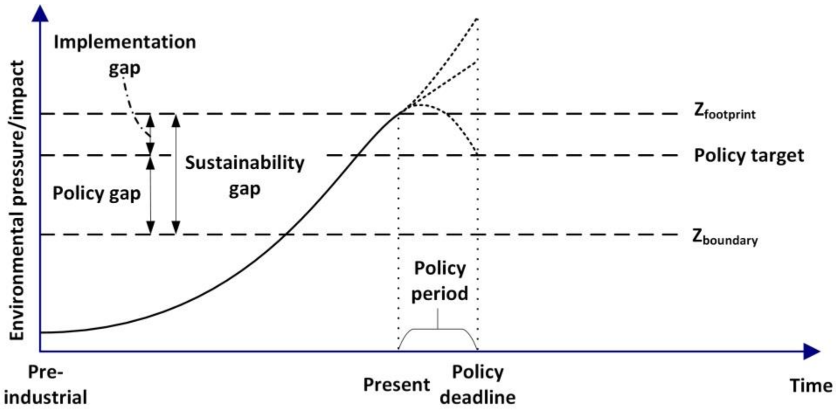

Figure 5.2. A schematic of the sustainability gap, policy gap, and implementation gap. Adapted from Fischer et al. (2007) and Nykvist et al. (2013).

5.5. Research agenda for strengthening the footprint–boundary environmental sustainability framework in future work

5.5.1. Development of measurable aggregated boundaries at multiple scales

It is unclear how regime shifts propagate across scales, and whether local and regional unsustainability necessarily gives rise to global transitions that imply an irreversible collapse worldwide (Hughes et al., 2013). Rockström et al. highlight that for some aggregated issues, such as water use, land use and aerosol loading, it matters where stressors exert negative effects; therefore, the associated environmental consequences are spatially varying and primarily limited to local area. The aerosol loading in East China, for instance, may have led to severe environmental and human health risks, but this hardly contributes to the aerosol loading in New Zealand. In this case, affecting in one region has no unambiguous direct relation to other regions.

As such, aggregated issues are unlikely to show strong evidence of global threshold behaviors (Rockström et al., 2009b); unless their heterogeneous impacts on local environment have been extensively replicated and ultimately spread worldwide (Lewis, 2012). Consequently, setting planetary boundaries merely and waiting until we approach them are dangerous and may significantly obscure the seriousness of environmental degradation at a regional or local scale. For example, while the planetary boundary for phosphorus has not yet been transgressed (Rockström et al., 2009a, 2009b), a striking fact which should not be neglected is that the absorptive capacity for phosphorus in two-thirds of the world's river basins has already been fully consumed (Hoekstra and Wiedmann, 2014).

This justifies the importance of developing measurable aggregated boundaries regionally or locally, which however remains largely unexplored in current PBF. As discussed, the biocapacity and water availability provide paradigms for the measurement of local and regional environmental boundaries. We argue that aggregating local or regional boundaries to the national level would allow for a reasonably refined estimate of national boundaries for those aggregated issues. This could be achieved by means of a bottom-up approach. The sensitivity to place of aggregated issues, however, constitutes a major constraint on applications of such an upscaling (Nykvist et al., 2013). Another challenge concerns the allocation problem (Heijungs and Frischknecht, 1998), as the real geographical scale of anthropogenic perturbation and associated impacts, which for instance can be a river basin, is very likely to go beyond national borders.

5.5.2. Partitioning of systemic planetary boundaries for sub-global assessments

On the other hand, it is also unclear how long the boundary exceedance actually takes to cause catastrophic environmental effects, even though a global threshold effect for systemic issues (climate change, ozone depletion, and ocean acidification) arguably exists regardless of where stressors are imposed (Nykvist et al., 2013; Rockström et al., 2009b). Such a transition is elusive and unpredictable, typically lagged by centuries, millennia, or even millions of years (Hughes et al., 2013), as evidenced in the observation that over the past two billion years global transitions rarely took place, with an estimate of five times merely (Barnosky et al., 2012). This is why the practitioners recently concede that exceeding one or few planetary boundaries is unlikely to give rise to disastrous consequences as immediate as previously thought (Hughes et al., 2013; Lenton and Williams, 2013).

Misinterpretation may occur if one misunderstands the precautionary principle that the planetary boundaries concept relies on and equates a surpassed boundary with a critical transition that corresponds to regime shifts—a sharp and persistent reorganization of the state of an ecosystem, which can hardly be anticipated or reversed by man (Brook et al., 2013). Besides, the global nature of systemic issues does not verify that all entities should take an equal responsibility for emission reduction—a politically salient issue that tends to trigger international instability. To start downscaling systemic boundaries for the allocation of responsibility, establishing internationally agreed criteria is a preparatory step towards a politically acceptable way, just like the distribution of CO_2 emission quotas (Germain and Van Steenberghe, 2003).

Any environmental agreement on the partitioning of systemic planetary boundaries requires negotiation and compromise among different levels of stakeholders such as governments, non-governmental organizations, corporations, and individual citizens. In the absence of reliable databases for local conditions, the partitioning of the "cake" can be first implemented nation by nation. Admittedly, there is more than one way to operationalize such a top-down process, such as on a population size base, a Gross Domestic Product (GDP) base, a territorial area base, or on other bases. Extending the national-scale boundary to sub-national scales will only be realized by a large number of dedicated personnel with sufficient technical and financial support. A schematic representation of the suggested bottom-up and top-down approaches for boundary scaling is given in Figure 5.3.

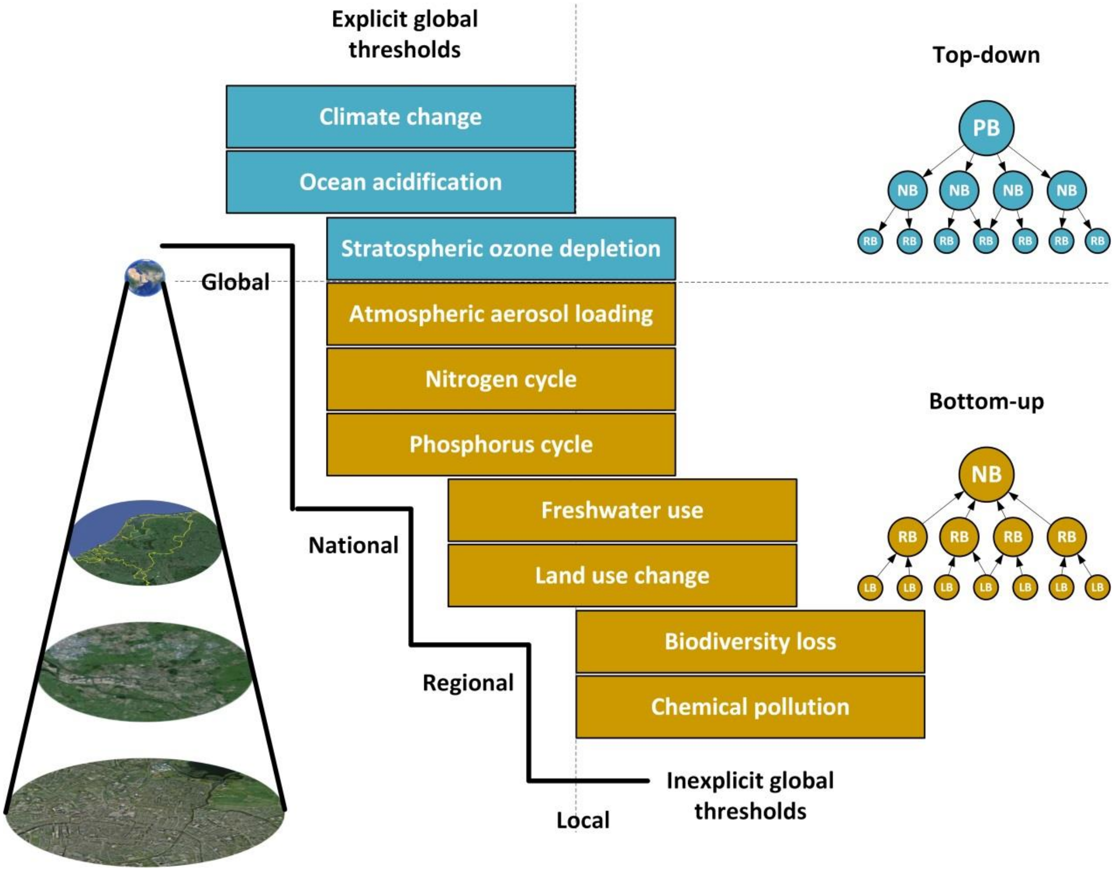

Figure 5.3. A schematic of the bottom-up and top-down approaches to boundary scaling. Adapted from Rockström et al. (2009b). The environmental issues in blue rectangles represent systemic issues, and those in brown rectangles represent aggregated issues. NB: national boundary; RB: regional boundary; LB: local boundary.

5.5.3. Harmonization of the footprint metric and the boundary metric

In concretizing the F–B ESA framework presented in the chapter, maintaining the harmonization between the footprint and boundary metrics deserves priority. We elaborate on this in two aspects: the harmonization of coverage and the harmonization of methodologies.

According to the coverage of major environmental concerns (Figure 5.4), one may easily come to the conclusion that as a whole there is substantial similarity between environmental footprints and planetary boundaries, because they both cover similar and wide-enough spectrums of environmental issues. Nevertheless, converting a footprint and a boundary into a common metric is probably incomplete, as in many cases multiple footprints are related to multiple boundaries. Although the inconsistency of the indicator coverage presented here does not invalidate the foundations and logics of the F–B ESA framework, the system boundaries of each pair of the indicators are better redefined without apparent overlap and inconsistency if the aim is to establish a one-to-one correspondence between the footprint and boundary metrics.

With respect to the obstacles to methodological harmonization, formally recognized approaches to the calculation of sub-global boundaries are still lacking. In contrast, despite the diversity of the footprint family, there has been an empirical principle for selection of appropriate methodologies at sub-global scales: the micro-scale (e.g., product, material) footprints are often subject to bottom-up life cycle assessment (LCA), the macro-scale (e.g., nation, continent) footprints generally commit to top-down input–output analysis (IOA), and the meso-scale (e.g., organization, community) footprints can be addressed by hybrid approaches that combine the strengths of both LCA and IOA (Fang et al., 2014; Peters, 2010). As a result, the ongoing efforts to quantify the boundary metric at sub-global scales should be undertaken in the usual impact systems that matches well with the relevant footprint accounting.

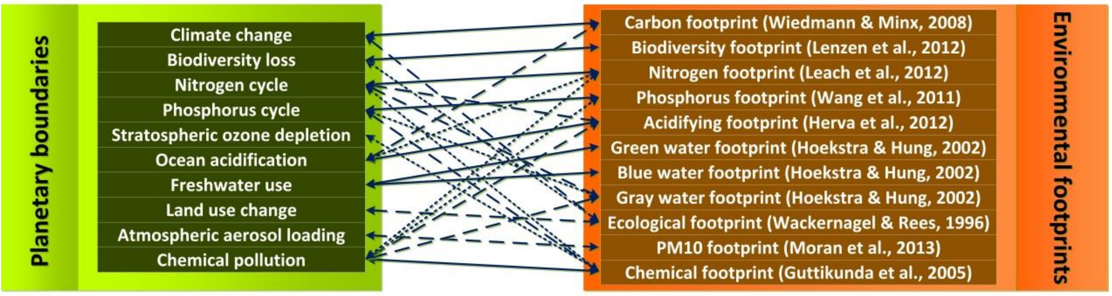

Figure 5.4. Thematic matching of environmental footprints and planetary boundaries. The solid line, long dashed line, and short dashed line represent the degree of matching from high to medium to low.

5.5.4. Trade-offs between different sustainability gaps

Even though in some cases the geographical link between two distant regions is weak, there is no doubt that environmental issues within the Earth's life-supporting systems are essentially interlinked and interactive, and hence cannot be uncoupled from each other (Biermann, 2012). The sustainability of a given region depends, directly or indirectly, on the sustainability of many other regions (Kissinger et al., 2011). In the context of globalization, transgressing one boundary may exert profound intraregional or interregional effects on other boundaries in ways that people do not expect. Thus, maintaining the safe operating space for a single issue without looking at the whole picture seems impractical and no longer a wise policy option. This finding suggests a great need not only for simultaneous assessment of the environmental sustainability of individual issues at different scales, but also for trade-offs between the many sustainability gaps where anthropogenic perturbation ought to be treated with a systematic view.

Such trade-offs can be made thoroughly by ascertaining all categories of environmental footprints and boundaries involved. One difficulty is due to the displacement and leakage effects (Erb et al., 2012), as improvements in some overstepped boundaries are often obtained at the expense of deteriorating other boundaries. In attempts to meet the policy demand for an overall picture of different environmental issues, weighting has been brought to attention with the argument that trade-offs, in many cases, cannot be tackled in a manageable and comprehensive way without some form of weighting (Ahlroth, 2014; Ridoutt and Pfister, 2013).

In contrast to the existing footprint family discourses where conceivable footprints are aggregated to yield a stand-alone, single-score footprint metric (Hadian and Madani, 2015; Ridoutt and Pfister, 2013), we argue for a composite sustainability index that results from weighting and aggregating diverse sustainability gaps into one equation from an integrated perspective. This is accompanied by a recognition that weighting footprints and boundaries simultaneously would offer a more meaningful evaluation of trade-offs than weighting either footprints or boundaries on their own, in particular when policy makers do need a direct comparison of options or entities in terms of their overall performance on environmental sustainability. Approaches to weighting typically include panel methods, distance-to-target, willingness to pay, and more (Ahlroth, 2014).

Weighting sustainability gaps could be considered as a practical possibility, whereas the weighted results should be interpreted with caution. Improper interpretation may violate the intention of the planetary boundaries concept, which is committed to a comprehensive set of non-weighted variables in order to capture diverse global environmental challenges instead of a single-value metric (Nykvist et al., 2013). More importantly, the weighting implicitly legitimates the substitutability of boundaries among environmental issues. While it seems likely to substitute some forms of environmental boundaries, basic life-supporting systems are almost impossible to substitute (Barbier et al., 1994; Moldan et al., 2012).

That is to say, ESA is also a substitution problem in addition to its scaling dimension. A precedent for this is the combination of ecological footprint and biocapacity into a single score, where the weighting scheme has always been steeped in controversy (Kitzes and Wackernagel, 2009; Lenzen and Murray, 2001). The critiques mainly arise from the misinterpretation it may create that the scarcity of carrying capacity for one land's footprint is always allowed to be counteracted by the unconsumed carrying capacity within the boundaries of other lands. Moreover, the lack of differentiation between aggregated issues (e.g., land use) and systemic issues (e.g., carbon emissions) represents another defect in the ecological footprint analysis (EFA), as well as in typical footprint family studies. A partial solution might be to present the results both at the aggregate and disaggregate levels in keeping with the divergent requirements of policy makers and scientists.

5.6. Conclusions

This chapter investigates the complementary linkages between environmental footprints and planetary boundaries originating from two leading communities in the fields of ecological and environmental sciences and doing something quite similar but with their own strengths and weaknesses and surprisingly lacking communication and mutual understanding. The environmental footprints are broadly accepted as a representative of pressure or impact in relation to resource extractions and hazardous emissions, and human knowledge of planetary boundaries provides a set of consensus-based estimates of the regenerative and absorptive capacity of the Earth's life-supporting systems. Although the conceptual roots, calculation methods and policy relevance of different footprints vary widely, in aggregate they show significant similarity to planetary boundaries in terms of environmental coverage.

Both tools are found to be limited in their ability to handle sustainability issues. On the one hand, footprint studies focus typically on measuring and minimizing environmental impacts without seeing if such operationalization is truly in a sustainable way, with some exceptions including the ecological, carbon, water, and chemical footprints, where global and regional threshold measurements are nevertheless far from satisfactory. Misleading conclusions and wrong decisions could be made in the case that the distinction between sustainable and unsustainable activities is vague, ambiguous, or missing at all. On the other hand, while a rough estimate of current human activities is provided in the existing planetary boundaries research besides threshold estimates, it is criticized for the sole use of expert knowledge and lack of quantitative consensus models, which likely lead to unreliable or even false results.

In view of the differing emphases and challenges of footprints and boundaries, it is our conviction that the two metrics should not be viewed as alternatives but rather as complements. The synthesizing of environmental footprints and planetary boundaries makes it possible to benchmark man's contemporary footprints against maximum sustainable footprints (Hoekstra and Wiedmann, 2014), and thereby to indicate the degree to which the functioning of Earth's life-supporting systems has been maintained or crossed. The suggested F–B ESA framework, in this sense, opens the way for a straightforward assessment of environmental sustainability—a non-negotiable prerequisite for the economic and social pillars of sustainable development (Goodland and Daly, 1996).

The growing sustainability gaps between numerous types of environmental burden and the Earth's finite carrying capacity call for a shift from EIA—which may not be informative for policy makers as well as consumers—to ESA, but also from focusing issues in isolation to addressing them simultaneously from an integrated perspective. Today's environmental unsustainability worldwide underpins the need for setting more practical and tangible policy targets for adaptation and mitigation, rather than for unrealistically preventing the overshoot of the Earth's capacity to regenerate resources and assimilate wastes. An example of this is the renegotiation of the "2 °C target" (Parry et al., 2009). Due to the complexity and uncertainty of the environment, a major challenge is how to make trade-offs among various sustainability gaps in support of optimal adaptation strategies in the context of global unsustainability.

We consider this to be a scale problem more than a substitution problem. The quantifications of both boundaries and footprints appear to be strongly scale-dependent (Hughes et al., 2013; Moran et al., 2008; Wiedmann and Lenzen, 2007). This is one reason to take the scale dimension into account when evaluating trade-offs between policy options with consequences for environmental sustainability. Another reason is that the non-transgression of one planetary boundary does not necessarily guarantee a sustainable society, because regional or local boundary exceedance may still give rise to irreversible environmental degradation that is detrimental or even disastrous to the population.

This is particularly true when it comes to aggregated issues that are spatially heterogeneous and local-to-regional in scale. The development of measurable local and regional boundaries is therefore needed. It could serve as a basis for ESA applied to the allocation of environmental responsibility for creating sustainable societies at multiple scales. Lessons can be learned from current methodological choices of environmental footprints. Even for systemic issues, which are believed to have a true global threshold effect, partitioning their planetary boundaries into national or sub-national shares still makes sense. This, however, might be more challenging because of the political attribute of implementing a top-down process that is possibly based on population, GDP, or area, rather than on real regional thresholds.

While the idea of relating descriptive indicators to capacity thresholds is actually not new, this chapter provides concrete discussions of how to bring together the two emerging research fields (environmental footprints and planetary boundaries) as a novel approach for ESA, thus contributing to the ever-developing sustainability discourse. Admittedly, there remain many gaps in our knowledge that may compromise the credibility and applicability of the F–B ESA framework proposed in the thesis. We have therefore gone on at length formulating a research agenda for the global community to continuously improve the performance of the F–B ESA framework on transparency and robustness. This requires a large research effort with contributions from a vast range of fields such as ecology, environmental science, earth science, system science, and social science, and because of this, we call for extensive interdisciplinary communication and collaboration among scientists in each of these disciplines.

References

Ahlroth, S., 2014. The use of valuation and weighting sets in environmental impact assessment. Resources, Conservation and Recycling 85, 34–41.

Allen, M., 2009. Tangible targets are critical. Nature Reports Climate Change 3, 114–115.

Barbier, E. B., Burgess, J. C., Folke, C., 1994. Paradise Lost? — The Ecological Economics of Biodiversity. Earthscan, London, UK.

Barnosky, A. D., Hadly, E. A., Bascompte, J., Berlow, E. L., Brown, J. H., Fortelius, M., Getz, W. M., Harte, J., Hastings, A., Marquet, P. A., Martinez, N. D., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J. W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D. P., Revilla, E., Smith, A. B., 2012. Approaching a state shift in Earth's biosphere. Nature 486, 52–58.

Biermann, F., 2012. Planetary boundaries and earth system governance: exploring the links. Ecological Economics 81, 4–9.

Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J. C., Wackernagel, M., Galli, A., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecological Indicators 24, 518–533.

Brook, B. W., Ellis, E. C., Perring, M. P., Mackay, A. W., Blomqvist, L., 2013. Does the terrestrial biosphere have planetary tipping points? Trends in Ecology & Evolution 28, 396–401.

Catton, W., 1986. Carrying Capacity and the Limits to Freedom. Social Ecology Session, 1, XI World Congress of Sociology. New Delhi, India.

Costanza, R., 2000. The dynamics of the ecological footprint concept. Ecological Economics 32, 341–345.

Costanza, R., Patten, B. C., 1995. Defining and predicting sustainability. Ecological Economics 15, 193–196.

Daily, G. C., Ehrlich, P. R., 1992. Population, sustainability, and Earth's carrying capacity. BioScience 42, 761–771.

Daly, H. E., 1990. Toward some operational principles of sustainable development. Ecological Economics 2, 1–6.

De Vries, W., Kros, J., Kroeze, C., Seitzinger, S. P., 2013. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Current Opinion in Environmental Sustainability 5, 392–402.

Ehrlich, P. R., 1982. Human carrying capacity, extinctions, and nature reserves. BioScience 32, 331–333.

Erb, K.-H., Haberl, H., Defries, R., Ellis, E. C., Krausmann, F., Verburg, P. H., 2012. Pushing the planetary boundaries. Science 338, 1419–1420.

Ewing, B. R., Hawkins, T. R., Wiedmann, T. O., Galli, A., Ertug Ercin, A., Weinzettel, J., Steen-Olsen, K., 2012. Integrating ecological and water footprint accounting in a multi-regional input–output framework. Ecological Indicators 23, 1–8.

Fang, K., Heijungs, R., 2015. Rethinking the relationship between footprints and LCA. Environmental Science & Technology 49, 10–11.

Fang, K., Heijungs, R., De Snoo, G. R., 2014. Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: overview of a footprint family. Ecological Indicators 36, 508–518.

Fischer, J., Manning, A. D., Steffen, W., Rose, D. B., Daniell, K., Felton, A., Garnett, S, Gilna, B., Heinsohn, R., Lindenmayer, D. B., MacDonald, B., Mills, F., Newell, B., Reid, J., Robin, L., Sherren, K., Wade, A., 2007. Mind the sustainability gap. Trends in Ecology & Evolution 22, 621–624.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, E, Giljum, S., 2012. Integrating ecological, carbon and water footprint into a "Footprint Family" of indicators: definition and role in tracking human pressure on the planet. Ecological Indicators 16, 100–112.

Gerbens-Leenes, W., Hoekstra, A. Y., Van der Meer, T. H., 2009. The water footprint of bioenergy. Proceedings of the National Academy of Sciences of the United States of America 106, 10219–10223.

Germain, M., Van Steenberghe, V., 2003. Constraining equitable allocations of tradable CO_2 emission quotas by acceptability. Environmental and Resource Economics 26, 469–492.

Goldfinger, S., Wackernagel, M., Galli, A., Lazarus, E., Lin, D., 2014. Footprint facts and fallacies: a response to Giampietro and Saltelli (2014) "Footprints to Nowhere". Ecological Indicators 46, 622–632.

Goodland, R., Daly, H., 1996. Environmental sustainability: universal and non-negotiable. Ecological Applications 6, 1002–1017.

Guttikunda, S. K., Tang, Y., Carmichael, G. R., Kurata, G., Pan, L., Streets, D. G., Woo, J.-H., Thongboonchoo, N., Fried, A., 2005. Impacts of Asian megacity emissions on regional air quality during spring 2001. Journal of Geophysical Research 110, D20301–D20301.

Hadian, S., Madani, K., 2015. A system of systems approach to energy sustainability assessment: Are all renewables really green? Ecological Indicators 52, 194–206.

Heijungs, R., De Koning, A., Guinée, J. B., 2014. Maximizing affluence within the planetary boundaries. The International Journal of Life Cycle Assessment 19, 1331–1335.

Heijungs, R., Frischknecht, R., 1998. A special view on the nature of the allocation problem. The International Journal of Life Cycle Assessment 3, 321–332.

Hellweg, S., I Canals, L. M., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science 344, 1109–1113.

Hoekstra, A. Y., 2009. Human appropriation of natural capital: a comparison of ecological footprint and water footprint analysis. Ecological Economics 68, 1963–1974.

Hoekstra, A. Y., Hung, P. Q., 2002. Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade. Value of Water Research Report Series (No. 11), UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

Hoekstra, A. Y., Mekonnen, M. M., 2012. The water footprint of humanity. Proceedings of the National Academy of Sciences of the United States of America 109, 3232–3237.

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., Richter, B. D., 2012. Global monthly water scarcity: blue water footprints versus blue water availability. PLoS One 7, e32688–e32688.

Hoekstra, A. Y., Wiedmann, T. O., 2014. Humanity's unsustainable environmental footprint. Science 344, 1114–1117.

Hughes, T. P., Carpenter, S., Rockström, J., Scheffer, M., Walker, B., 2013. Multiscale regime shifts and planetary boundaries. Trends in Ecology & Evolution 28, 389–395.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, USA.

Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., McCarthy, J. J., Schellnhuber, H. J., Bolin, B., Dickson, N. M., Faucheux, S., Gallopin, G. C., Grübler, A., Huntley, B., Jäger, J., Jodha, N. S., Kasperson, R. E., Mabogunje, A., Matson, P., Mooney, H., Moore, B. III., O'Riordan, T., Svedin, U., 2001. Environment and development: sustainability science. Science 292, 641–642.

Kissinger, M., Rees, W. E., Timmer, V., 2011. Interregional sustainability: governance and policy in an ecologically interdependent world. Environmental Science & Policy 14, 965–976.

Kitzes, J., Wackernagel, M., 2009. Answers to common questions in ecological footprint accounting. Ecological Indicators 9, 812–817.

Kosoy, N., Brown, P. G., Bosselmann, K., Duraiappah, A., Mackey, B., Martinez-Alier, J., Rogers, D., Thomson, R., 2012. Pillars for a flourishing Earth: planetary boundaries, economic growth delusion and green economy. Current Opinion in Environmental Sustainability 4, 74–79.

Kratena, K., 2004. 'Ecological value added' in an integrated ecosystem–economy model—an indicator for sustainability. Ecological Economics 48, 189–200.

Lancker, E., Nijkamp, P., 2000. A policy scenario analysis of sustainable agricultural development options: a case study for Nepal. Impact Assessment and Project Appraisal 18, 111–124.

Laurent, A., Olsen, S. I., Hauschild, M. Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability. Environmental Science & Technology 46, 4100–4108.

Leach, A. M., Galloway, J. N., Bleeker, A., Erisman, J. W., Kohn, R., Kitzes, J., 2012. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. Environmental Development 1, 40–66.

Lenton, T. M., Williams, H. T., 2013. On the origin of planetary-scale tipping points. Trends in Ecology & Evolution 28, 380–382.

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A., 2012. International trade drives biodiversity threats in developing nations. Nature 486, 109–112.

Lenzen, M., Murray, S. A., 2001. A modified ecological footprint method and its application to Australia. Ecological Economics 37, 229–255.

Lewis, S. L., 2012. We must set planetary boundaries wisely. Nature 485, 417–417.

Liu, C., Kroeze, C., Hoekstra, A. Y. Gerbens-Leenes, W., 2012. Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. Ecological Indicators 18, 42–49.

Meadows, D. H., Meadow, D. L., Randers, J., Behrens, W., 1972. The Limits to Growth. Universe Books, New York. USA.

Minx, J., Baiocchi, G., Wiedmann, T., Barrett, J., Creutzig, F., Feng, K., Förster, M., Pichler, P.-P., Weisz, H., Hubacek, K., 2013. Carbon footprints of cities and other human settlements in the UK. Environmental Research Letters 8, 035039–035039.

Moldan, B., Janoušková, S., Hák, T., 2012. How to understand and measure environmental sustainability: Indicators and targets. Ecological Indicators 17, 4–13.

Molden, D., 2009. The devil is in the detail. Nature Reports Climate Change 3, 116–117.

Moran, D. D., Wackernagel, M., Kitzes, J. A., Goldfinger, S. H., Boutaud, A., 2008. Measuring sustainable development—Nation by nation. Ecological Economics 64, 470–474.

Niccolucci, V., Bastianoni, S., Tiezzi, E. B. P., Wackernagel, M., Marchettini, N., 2009. How deep is the footprint? A 3D representation. Ecological Modelling 220, 2819–2823.

Nykvist B, Persson Å, Moberg F, Persson, L., Cornell, S., Rockström, J., 2013. National Environmental Performance on Planetary Boundaries: a Study for the Swedish Environmental Protection Agency. Stockholm Resilience Center & Stockholm Environment Institute, Stockholm, Sweden.

Parry, M., Lowe, J., Hanson, C., 2009. Overshoot, adapt and recover. Nature 458, 1102–1103.

Peters, G. P., 2010. Carbon footprints and embodied carbon at multiple scales. Current Opinion in Environmental Sustainability 2, 245–250.

Rees, W. E., 1992. Ecological footprint and appropriated carrying capacity: what urban economics leaves out. Environment and Urbanization 4, 121–130.

Rees, W. E., 1996. Revisiting carrying capacity: area-based indicators of sustainability. Population and Environment 17, 195–215.

Ridoutt, B. G., Pfister, S., 2013. Towards an integrated family of footprint indicators. Journal of Industrial Ecology 17, 337–339.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., De Wit, C. A., Hughes, T., Van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J. A., 2009a. A safe operating space for humanity. Nature 461, 472–475.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., De Wit, C. A., Hughes, T., Van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009b. Planetary boundaries: exploring the safe operating space for humanity. Ecology and Society 14, 32–32.

Rogelj J., McCollum, D., O'Neill, B. C., Riahi K., 2013. 2020 emissions levels required to limit warming to below 2 °C. Nature Climate Change 3, 405–412.

Smeets, E., Weterings, R., 1999. Environmental Indicators: Typology and Overview. Technical Report (No. 25). TNO Centre for Strategy, Technology and Policy, The Netherlands.

Steffen, W., Stafford Smith, M., 2013. Planetary boundaries, equity and global sustainability: why wealthy countries could benefit from more equity. Current Opinion in Environmental Sustainability 5, 403–408.

UNEP, 2013. The Emissions Gap Report 2013: A UNEP Synthesis Report. http://www.unep.org/pdf/UNEPEmissionsGapReport2013.pdf.

Wackernagel, M., Rees, W. E., 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society, Gabriola Island, British Columbia, Canada.

Wackernagel, M., Rees, W. E., 1997. Perceptual and structural barriers to investing in natural capital: Economics from an ecological footprint perspective. Ecological Economics 20, 3–24.

Wang, F., Sims, J. T., Ma, L., Ma, W., Dou, Z., Zhang, F., 2011. The phosphorus footprint of China's food chain: implications for food security, natural resource management, and environmental quality. Journal of Environmental Quality 40, 1081–1089.

Wiedmann, T., Lenzen, M., 2007. On the conversion between local and global hectares in Ecological Footprint analysis. Ecological Economics 60, 673–677,

Wiedmann, T., Minx, J., 2008. A definition of 'carbon footprint'. In: Pertsova, C. C. (Ed.), Ecological Economics Research Trends. Nova Science Publishers, Hauppauge, New York, USA, pp. 1–11.

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proceedings of the National Academy of Sciences of the United States of America 112, 6271–6276.

Zijp, M. C., Posthuma, L., Van de Meent, D., 2014. Definition and applications of a versatile chemical pollution footprint methodology. Environmental Science & Technology 48, 10588−10597.