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

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Chapter 1

General introduction

1.1. The origin of environmental footprints

Significant changes to the Earth's environment have been witnessed over the past decades, with consequences that are undesirable or even disastrous for humanity (Barnosky et al., 2012; Scheffer et al., 2009). This has led to a transition from the Holocene—a geological epoch that spanned a long period of time—to the Anthropocene—a new era in which human disturbance is greatly eroding the stability and resilience of the Earth system (Crutzen, 2002; Steffen et al., 2011). In striving to preserve the planet as a pleasant place for living and as a source of human welfare in this challenging era, there is a great need for novel approaches to modeling anthropogenic effects that are the key to identifying the driving forces of contemporary environmental change.

Ecological footprint analysis (EFA) was originally introduced and advocated to evaluate the effects of anthropogenic activities on urban sustainability (Rees, 1992). It compiled, on an area basis, the inputs of biological resources and the outputs of carbon emissions (i.e., the ecological footprint) and compared to the regenerative and assimilative capacity of urban ecosystems (i.e., the biocapacity), indicating whether or not the situation remains sustainable (Rees, 1997). At the human–environment interface, six types of land use on which human disturbance is most likely to place have been taken into account, including cropland, grassland, fishing ground, woodland, built-up land, and carbon uptake land. These relate to six ecosystem services respectively: plant-based food production, animal-based food production, fish-based food production, timber production, living space supply, and carbon dioxide (CO_2) sequestration.

In view of the success in raising public awareness of environmental issues and in evoking effective policy actions, Wackernagel and Rees (1997) have implemented an extension to the methodological application of the EFA, particularly pinpointing nation-wide economy. In the latest edition of the National Footprint Accounts (NFA), the ecological footprint is defined as the area of biologically productive space required to produce the resources consumed and to absorb the waste generated, considering the prevailing technology and resources management practices (Borucke et al., 2013). The biocapacity, which can be probably traced back to attempts to quantify human carrying capacity (e.g., Cohen, 1995; Ehrlich, 1982), is conceived in such a way that it can provide a region-specific threshold value for the ecological footprint of a given population. The comparison of the ecological footprint and biocapacity makes it possible to contrast sustainable and unsustainable consumption or production in an explicit manner.

1.2. The development of environmental footprints

Despite the worldwide popularity gained in the past two decades, the EFA is found incapable of capturing all aspects of human disturbance to the biosphere (Goldfinger et al., 2014), let alone to the atmosphere and hydrosphere. For this reason, a growing number of footprint-style indicators have been developed in order to complement the EFA in different dimensions. Examples in the environmental domain include the water footprint (Hoekstra and Hung, 2002), the energy footprint (Stöglehner, 2003), the carbon footprint (Wiedmann and Minx, 2008), the chemical footprint (Hitchcock et al., 2011), the phosphorus footprint (Wang et al., 2011), the biodiversity footprint (Lenzen et al., 2012), the nitrogen footprint (Leach et al., 2012), the land footprint (Weinzettel et al., 2013), the material footprint (Wiedmann et al., 2015), the resource footprint (Huysman et al., 2014), and so on.

In keeping with the ongoing expansion of the footprint family (Fang et al., 2014; Galli et al., 2012), the underlying methodologies are currently undergoing rapid development. In addition to the NFA, life cycle assessment (LCA) (Weidema et al., 2008), input–output analysis (IOA) (Hertwich and Peters, 2009), material flow analysis (MFA) (Schoer et al., 2012) and emergy-based (Zhao et al., 2005) and exergy-based methods (Chen and Chen, 2007) have proved useful in calculating different environmental footprints at scales ranging from single products, processes, organizations, industries, nations, even to the whole human economy. Recently emerging hybrid approaches that take advantage of both LCA and IOA have shown great potential for meso-level footprint accounting for which well-established methods are lacking. As a whole, the choices of appropriate methods are playing a central role in quantitative footprint studies.

The footprint family concept has attracted considerable interest as it offers the scientific community an opportunity to achieve simultaneous measurement of various environmental footprints with implications for trade-off issues (e.g., De Meester et al., 2011; Ridoutt et al., 2014). By structuring a specified footprint family based on LCA (De Benedetto and Klemeš, 2009) or on multi-regional input–output (MRIO) models (Ewing et al., 2012), for instance, current accounts for selected footprints have been conceptually integrated into single unified frameworks that would allow for greater transparency and consistency. A further step towards policy-relevant research is to develop an integrated footprint family that is supposed to encompass the complexity of some highly heterogeneous environmental issues, such as climate change (carbon footprint), water use (water footprint), land use (land footprint), and material use (material footprint).

1.3. Debates on environmental footprints

Since the first emergence of the ecological footprint, the term "footprint" has stimulated scientific debates, representing important steps in the ongoing discourse on sustainability (e.g., Hoekstra and Wiedmann, 2014; Kitzes et al., 2009). Of particular concern is what actually counts as a footprint. Efforts have been made to lay the foundation for a widely accepted footprint definition (e.g., Hammond, 2007; Pelletier et al., 2014). At least five competing criteria are evidently available in the literature for definition of footprints:

a) Footprints are indicators that express their results in an area-based metric unit. Clearly the ecological footprint is the most obvious example of this. Many other well-known indicators, like the carbon footprint and the water footprint, would fall outside the scope by this definition.

b) Footprints are indicators that are intended for easy communication of results to the general public, policy makers, or other decision-makers. Indicators that aim to inform scientists and engineers, for instance, would in that case not be considered as a footprint. An example of such indicators is the eutrophication potential.

c) Footprints are indicators that include a supply chain or that even take a full life cycle perspective, i.e., indicators that only look at impacts of a country, company, for instance, without including at least the upstream impacts would be disqualified from the footprint family with this categorization.

d) Footprints are indicators that apply to the macro, economy-wide scale, in contrast to, for instance, LCA that studies one functional unit (e.g., kg) of a product.

e) Footprints are indicators that have the word "footprint" in their name. This criterion is based on an accidental nomenclature but many footprint users implicitly stick to. It excludes, for instance, those studies that account for water footprint but refer to this as virtual water or embodied water.

It is necessary to recognize further that a single footprint indicator may differ from another that has the same name but a different logic. For instance, the difference between volumetric water footprint and scarcity-based water footprint has been a subject of intense debate (Berger and Finkbeiner, 2013). This highlights the importance of categorization in systematizing the footprint family—a topic that has grown in interest in recent years (Čuček et al., 2012). In addition, while integrating different footprint results, by using weighting factors, into a single composite metric is appealing from a user-perspective, the scientific robustness and certainty of such a step are disputable, as any weighting schemes inevitably involve subjective judgments and are therefore prone to a lot of uncertainty (Huppes et al., 2012). The core of this challenge is the trade-offs between aggregate and disaggregate measures of environmental footprints (Fang and Heijungs, 2015).

1.4. The relation to life cycle assessment

Discussions on the close connection between environmental footprints and LCA have spawned an enormous literature (e.g., Hoekstra, 2015; Lenzen, 2014). A large number of pilot studies have provided concrete evidence of how LCA frameworks, in particular life cycle impact assessment (LCIA), allow various footprint indicators to be suited for environmental impact assessment (EIA) (e.g., Castellani and Sala, 2012; Huijbregts et al., 2008). Given that the footprint community has indeed learned and borrowed much from LCA knowledge, some LCA experts argue that all footprint accounts should be exclusively on an LCA basis (Ridoutt et al., 2015), in the hope that the much broader appeal of footprint indicators could, in turn, facilitate the diffusion of life cycle thinking, particularly for non-LCA experts (Ridoutt and Pfister, 2013; Weidema et al., 2008). In that case, LCA is meant to replace or supersede all other footprinting methods and to be the "golden standard".

However, the relationship between environmental footprints and LCA is not as simple as it may seem. While being similar in many key elements, environmental footprints differ from LCA in that they can be operationalized in contexts where there is no clear life cycle or even without an LCA. This can be exemplified by the case of the NFA calculations, where data gaps constitute a major challenge to the use of LCA for nation-wide economy (Hellweg and Milà i Canals, 2014). Moreover, there are certain important types of issues for which environmental footprints are desirable while an LCA is not or only partially suitable, as proved by the risk of double counting in large-scale LCA (Lenzen et al., 2007), and vice versa, some typical impact categories (e.g., ozone depletion, ionizing radiation) are out of the scope of the footprint family in its present form. These discrepancies observed suggest that environmental footprints may preferably have a different orientation from LCA.

1.5. The relation to planetary boundaries

With the latest scientific knowledge, the planetary boundaries framework (PBF) defines the global-scale safe operating space for humanity by determining the difference between the current and threshold values for several environmental issues (Rockström et al., 2009; Steffen et al., 2015). The PBF, in this sense, has much in common with the EFA because both of them are well suited for monitoring the extent to which humanity is approaching or exceeding biophysical limits. Yet, this does not mean that there is no difference between the PBF and the EFA. Their differing optimal scales present one example, in which the former is primarily limited to the global scale with the aim of supporting global sustainability goals and pathways, whereas the latter has a far wider range of applications and thus can be applied to environmental sustainability assessment (ESA) at sub-global scales (e.g., cities, nations).

In contrast to the ecological footprint, many footprint indicators, especially those based on LCA, do not include a comparison to any reference conditions, although this is increasingly being perceived as essential for ESA (e.g., Hoekstra, 2015; Moldan et al., 2012). For this reason, allocating planetary boundaries to the national- or regional-scale shares in comparison to environmental footprints may be a novel way to enhance the policy relevance of footprint studies (Fang et al., 2015). A main challenge arises from the fact that not all environmental issues are likely to show explicit threshold behaviors at sub-global scales. Meanwhile, lots of well-grounded footprint models would allow the PBF to have more accurate and reliable estimates of environmental pressures or impacts due to human activities at multiple scales. All this calls for a deeper understanding of the synergies between environmental footprints and planetary boundaries.

1.6. Research questions

The aims of the thesis are to provide novel insights into the ongoing discourse on environmental footprints and to bring clarity to a number of important theoretical and methodological issues which pose substantial barriers to the development of footprint indicators. On the basis of the brief introduction to the background, we identify the following research questions that will be answered in this thesis:

RQ1: Does it make sense to bring together different environmental footprints into a unified framework?

RQ2: How to make use of a selection of environmental footprints to constitute a truly integrated footprint family?

RQ3: Is life cycle assessment a necessity for accounting for environmental footprints?

RQ4: What are the complementarities of environmental footprints and planetary boundaries?

RQ5: How to allocate planetary boundaries to nations and how does this relate to nation-specific environmental sustainability assessment?

1.7. Outline of the thesis

In accordance to the research questions presented, this work of thesis comprises five thematic chapters (**Chapter 2–6**), together with an introductory chapter (**Chapter 1**) and a concluding chapter (**Chapter 7**), as illustrated in Figure 1.1.

Chapter 2 develops a conceptual framework for a footprint family that consists of the ecological, energy, carbon and water footprints. A comparative analysis of the four environmental footprints is performed, with emphases on their characteristics in some key aspects. By evaluating the performance of the footprint family on data availability, coverage complementarity, methodological consistency and policy relevance, the four footprint indicators are found to be complementary in assessing human pressures or impacts associated with natural resource extractions and hazardous emissions. The present footprint family captures a broad spectrum of sustainability issues and is thus able to offer policy makers a more complete picture of human-induced environmental change particularly at the national level than single footprints.

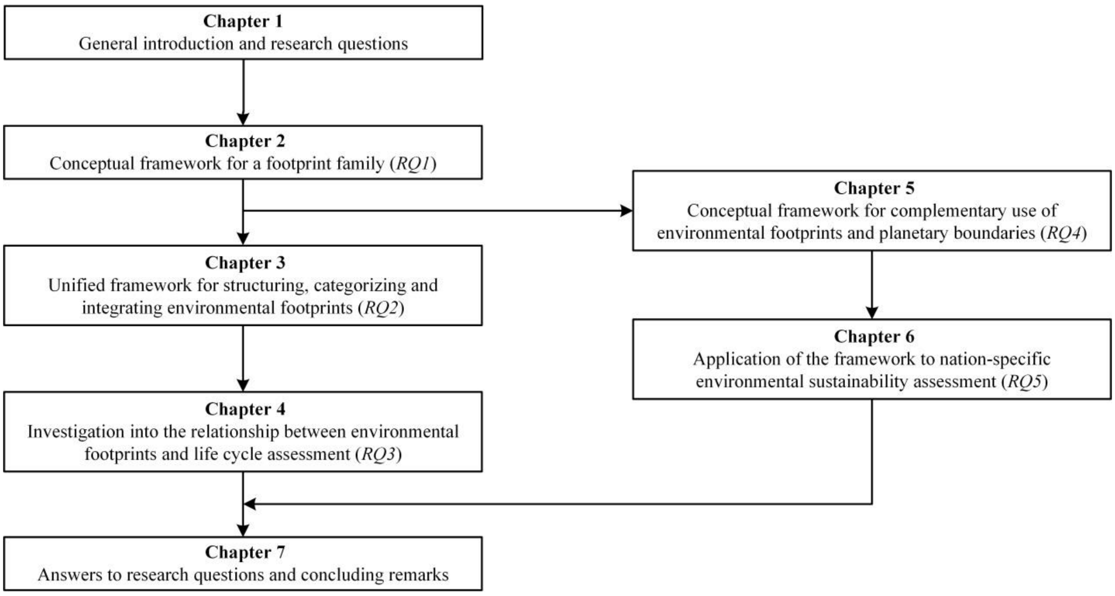

Figure 1.1. Outline of the thesis.

Chapter 3 investigates the roles of inventory schemes and impact characterization schemes in shaping footprint indicators, and concludes that within a single footprint, environmental exchange (extractions and emissions) is addressed either at the inventory level or at the impact assessment level. As such, a two-category framework is proposed, whereby existing environmental footprints can be classified into the inventory-oriented category and the impact-oriented category. While both categories have been found simultaneously in each of the carbon, water, land and material footprints in the literature, a truly integrated footprint family could be achieved only if all environmental footprints involved are impact-oriented. A unified framework for characterization, normalization and weighting of the impact-oriented footprints is established, with the aim of assisting policy makers in modeling the overall environmental impacts of single products, organizations, nations, or even the whole human economy.

Chapter 4 explores the tangled relationship between environmental footprints and LCA from different angles. On the one hand, footprint indicators could benefit from the use of LCIA elements. The important contribution of life cycle characterization modeling to the scientific foundation of the carbon footprint is discussed. With examples of the carbon and material footprints, it is strongly evident that the procedures for inventory aggregation can be improved by substitution of science-based characterization factors for arbitrary weighting factors. On the other hand, an analysis of several limitations of LCA in footprint accounting is conducted. It is demonstrated that narrowing environmental footprints down to an LCA context could create blind spots, where either inventory analysis and impact characterization are difficult to handle due to lack of data, or double counting of impacts occurs due to the inherent limits of LCA at the meso level.

Chapter 5 uncovers the complementary linkages between environmental footprints and planetary boundaries in support of ESA. By presenting a set of consensus-based estimates of the regenerative and absorptive capacity on the global scale, the PBF is found able to benchmark environmental footprints against reference conditions and, in reverse, many well-grounded footprinting methods could provide the PBF with more accurate and reliable estimates of contemporary anthropogenic interference. A framework for the complementary use of environmental footprints and planetary boundaries is therefore proposed, where sustainability gap is referred to as means to understand the difference between current magnitudes of human disturbance and finite biophysical thresholds. The footprint–boundary (F–B) ESA framework makes sense as it represents an important shift in focus, from EIA to ESA.

Chapter 6 conducts an empirical analysis of the F–B ESA framework, with a particular focus on its application at the national level. By using the latest datasets available, the planetary boundaries for carbon emissions, water use and land use are allocated to 28 selected countries in comparison to the respective national environmental footprints. The environmental sustainability ratio (ESR)—an internationally comparable indicator that communicates the sustainability gap in relative terms—allows one to map the transgression or reserve of nation-specific environmental boundaries for the 28 countries, visualizing how far countries are from their respective environmental boundaries. Multiple regression analysis shows that the worldwide unsustainability of carbon emissions is largely driven by economic development, while resource endowments play a central role in explaining national performance on water and land use.

Chapter 7 presents a synthesis of the answers to the research questions, followed by a general discussion and a research agenda for future work.

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