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Methodological and Ideological Options

Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–boundary environmental sustainability assessment framework

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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 paper 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 benefits from well-grounded footprint models which allow for more accurate and reliable estimates of human pressure 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 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.

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, however, seems 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 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., in press), and so on.

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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,b). 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 papers that address environmental footprints together with planetary boundaries employ different principles, frameworks, and terminologies. Our paper 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 the paper is structured as follows: Section 2 provides evidence on the importance of the planetary boundaries concept for making environmental footprints policy-relevant; Section 3, on the contrary, investigates the role of environmental footprints in improving the scientific robustness of the planetary boundaries framework; Section 4 demonstrates the benefits of jointly defining environmental sustainability; Section 5 proceeds with a detailed discussion of the challenges of synthesizing the footprint and boundary metrics and how these inform a research agenda.

2. Why Knowledge of Planetary Boundaries is Important for Making Environmental Footprints Policy-relevant

Many environmental footprints have proven useful in measuring the environmental pressure 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 simply minimize their environmental footprints, for which many footprint users concentrate on, but make sure these footprints stay within the planetary boundaries, for which this is central to 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 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 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.

3. Why Environmental Footprints are Important for Making the Planetary Boundaries Framework 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 exploring 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 environmental conditions. 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 planetary boundaries framework.

We will 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