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Review

Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: Overview of a footprint family

Kai Fang*, Reinout Heijungs, Geert R. de Snoo

Institute of Environmental Sciences, Faculty of Science, Leiden University, 2333CC Leiden, The Netherlands

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ABSTRACT

Over the past two decades, a continuously expanding list of footprint-style indicators has been introduced to the scientific community with the aim of raising public awareness of how humanity exerts pressures on the environment. A deeper understanding of the connections and interactions between different footprints is required in an attempt to support policy makers in the measurement and choice of environmental impact mitigation strategies. Combining a selection of footprints that address different aspects of environmental issues into an integrated system is, therefore, a natural step. This paper starts with the idea of developing a footprint family from which most important footprints can be compared and integrated. On the basis of literature review in related fields, the ecological, energy, carbon, and water footprints are employed as selected indicators to define a footprint family. A brief survey is presented to provide background information on each of the footprints with an emphasis on their main characteristics in a comparative sense; that is, the footprints differ in many aspects more than just the impacts they are addressed. This allows the four footprints to be complementarily used in assessing environmental impacts associated with natural resource use and waste discharge. We evaluate the performance of the footprint family in terms of data availability, coverage complementarity, methodological consistency, and policy relevance and propose solutions and suggestions for further improvement. The key conclusions are that the footprint family, which captures a broad spectrum of sustainability issues, is able to offer a more complete picture of environmental complexity for policy makers and, in particular, in national-level studies. The research provides new insights into the distinction between environmental impact assessment and sustainability evaluation, properly serving as a reference for multidisciplinary efforts in estimating planetary boundaries for global sustainability.

Contents

* Corresponding author. Tel.: +31 71 5271486; fax: +31 71 5277434.
E-mail address: fang@cml.leidenuniv.nl (K. Fang).

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1. Introduction

Over the past decades, our Earth has witnessed a significant shift from local environmental issues to global environmental change associated with an irreversible decline in natural capital stocks and ecosystem services on a global scale (Oosthoek and Gills, 2005). In striving to monitor the pressures humanity exerts on the environment, an integrated system where different impact categories can be measured through a set of appropriate indicators is needed (Giljum et al., 2011). The indicators of footprints have the potential to constitute a series of integrated systems with the purpose of providing a more complete picture of environmental complexity (Ridoutt and Pfister, 2013).

The concept of "footprint" originates from the idea of ecological footprint which was formally introduced to the scientific community in the 1990s (Rees, 1992, 1996; Wackernagel and Rees, 1996, 1997; Wackernagel et al., 1999a,b). Since then, many different footprint-style indicators have been created and became complementary to the ecological footprint during the last two decades including the energy footprint (Wackernagel and Rees, 1996), the water footprint (Hoekstra and Hung, 2002), the emergy footprint (Zhao et al., 2005), the exergy footprint (Chen and Chen, 2007), the carbon footprint (Wiedmann and Minx, 2008), the biodiversity footprint (Yaap et al., 2010), the chemical footprint (Panko and Hitchcock, 2011), the phosphorus footprint (Wang et al., 2011), the nitrogen footprint (Leach et al., 2012), and so on.

Nowadays, footprint indicators have become colloquial and ubiquitous for researchers, consultants and policy makers, and the implications for sustainability and human well-being have been investigated from different perspectives with an increasing interest in similarities, differences, and interactions between some selected footprints. Nevertheless, there is not yet a completely satisfactory and generally accepted footprint that can solely represent the overall impacts of human activities as the "golden standard" indicator (Huijbregts et al., 2010; Rees, 2002). Therefore, it seems to be a natural step to move toward an integrated system of footprint indicators. Following Galli et al. (2012), we refer to this as, namely, the "footprint family". The concept of a footprint family has only been preliminarily applied in that a very limited number of papers have dealt with it. Further research is thus required to improve transparency, consistency and scientific robustness of this topic.

The aim of this paper is to further operationalize the footprint family concept. To that end, this paper starts from a review of the existing literature on the combination of different footprints. We then elaborate on a specific footprint family with the most important, potential members and present a brief survey of those footprints with reference to their definitions, developments, and applications. The main characteristics of each footprint are summarized through a comparison of key issues with particular emphasis on methodological options at different scales. This is followed by a performance evaluation of the footprint family in different respects. The remainder of the paper proposes suggestions for improving the footprint family and draws conclusions.

2. Review of the literature on combining footprint indicators

This section is intended to provide background on the criterion for selecting footprints, not as a complete review. The term "footprint family" was first advocated simultaneously and independently by Giljum et al. (2008) and Stoeglehner and Narodoslawsky (2008). Subsequently, a landmark work on this topic is being undertaken by the OPEN: EU Project within the Seventh Framework Program, integrating the ecological, carbon, and water footprints into a footprint family in collaboration with an environmentally-extended multiregional input–output (MRIO) model (Galli et al., 2012, 2013).

Some other studies have discussed similar topics without mentioning the term "footprint family". For instance, De Benedetto and Klemeš (2009) designed a composite footprint indicator as a single measure for the sustainability of a given option. Niccolucci et al. (2010) developed an integrated footprint-based approach for environmental labeling of products. Herva et al. (2011) reviewed a series of environmental indicators and proposed the ecological and carbon footprints to be the most appealing indicators for enterprises. Čuček et al. (2012a) presented a comprehensive overview of the environmental, social, and economic footprints that can be used to measure the three pillars of sustainability. Steen-Olsen et al. (2012) used a MRIO model to quantify the total environmental pressures due to consumption in the EU by calculating the carbon, water, and land footprints. Fang et al. (2013) presented a critique on some of these integration schemes.

A review of the existing literature that compares or integrates multiple footprints is shown in Table 1. As we see, the environmental pillar of sustainability is much better covered than the social and economic pillars, so we will restrict the discussion of footprints in the environmental domain. The social and the economic footprints (Čuček et al., 2012b), for instance, are outside the scope of our analysis.

3. Elaboration of a footprint family

A footprint family consists of a number of members, each of which is a single-dimensional footprint. In this section, we will discuss the most important potential members with an emphasis on their characteristics in a comparative sense.

3.1. Selection of footprint indicators

The composition of a footprint family may vary depending on the relevance of the impact categories addressed (Ridoutt and Pfister, 2013). In principle, any two or more footprint indicators