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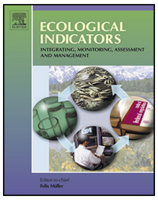

Review

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.

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* 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

Table 1
Overview of the literature that compares or integrates footprint indicators.

Reference	Ecological	Carbon	Water	Energy	Nitrogen	Biodiversity	Land	Phosphorus	Waste	Material	Emission	Social	Economic
Chakraborty and Roy (2013)		×		×									
Cranston and Hammond (2012)	×	×		×									
Čuček et al. (2012a)	×	×	×	×	×	×	×					×	×
Čuček et al. (2012b)		×			×								
Curry and Maguire (2011)	×	×											
De Benedetto and Klemeš (2009)		×	×	×							×		
Del Borghi et al. (2013)		×	×										
Ewing et al. (2012)	×		×										
Fang et al. (2013)	×	×	×	×									
Galli et al. (2012)	×	×	×										
Galli et al. (2013)	×	×	×										
Giljum et al. (2011)	×	×	×										
Hanafiah et al. (2010)	×			×	×			×					
Hanafiah et al. (2012)	×			×		×							
Herva et al. (2011)	×	×	×										
Herva et al. (2012)	×			×									
Hoekstra (2009)	×		×										
Hubacek et al. (2009)	×		×										
Jess (2010)	×			×					×				
Lenzen et al. (2012)	×	×	×										
Li et al. (2007)	×			×									
Moran et al. (2013)	×	×	×			×				×			
Page et al. (2012)		×	×										
Steen-Olsen et al. (2012)		×	×				×						
Xue and Landis (2010)		×			×								
Total	18	17	15	10	4	3	2	1	1	1	1	1	1

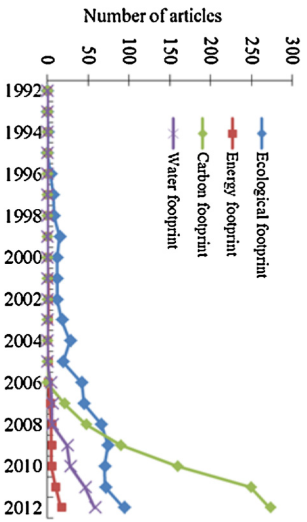

Fig. 1. Number of articles with the topic of "ecological footprint", "energy footprint", "carbon footprint", and "water footprint", respectively, delivered by global scholars from 1992 to 2012 by searching the Web of Science on 2013-01-04.

could be considered as a footprint family. However, given the fact that there are a variety of footprint indicators that measure single or collective pressures arising from production and consumption, we have to choose some of them to define a specific footprint family which is expected to address some significant anthropogenic impacts on major ecosystem compartments of the Earth-system.

As is clear from Table 1, the ecological, energy, carbon, and water footprints rank as the most important footprint indicators in the existing literature. This is partially because they are in close relation with the four worldwide concerns over threats to human society: food security, energy security, climate security, and water security (Mason and Zeitoun, 2013). Their frequencies of occurrence in scientific literature show a similar trend of increasing popularity during the period of 1992–2002 (Fig. 1). The total number of articles with the topic of "ecological footprint", "energy footprint", "carbon footprint", and "water footprint" reaches 598, 50, 839 and 172, respectively, while the number of papers for the rest of the footprints listed in Table 1 is only 39. Notably, the statistics of the carbon footprint began to soar in 2007 and have even exceeded that of the ecological footprint since 2009. In this paper, we make a selection of footprint indicators by combining the ecological, energy, carbon, and water footprints as potential members into a footprint family.

3.2. *Survey of selected footprints*

3.2.1. *Ecological footprint*

The ecological footprint is well-known as an effective communication tool for raising public awareness of the environmental impacts resulting from production and consumption. It was originally defined as a measure of the amount of ecologically productive land and water required to supply a specific activity with resources consumed and carbon dioxide (CO_2) generated (Monfreda et al., 2004; Wackernagel and Rees, 1996). Recently, it has been shifted to measure the land use that is required for population activities taking place on the biosphere within a given year while considering the prevailing technology and resource management of that year (Bastianoni et al., 2012; Borucke et al., 2013).

The methodology of the ecological footprint is included in a standardization process directed by the Global Footprint Network (GFN). The most widely used approach for the ecological footprint practitioners and users is the National Footprint Accounts (NFA), which is developed and maintained by the GFN. The NFA has been applied in more than 200 countries, serving as an essential database for the Living Planet Report that is prepared by a number of the world's top organizations (WWF, 2012). A detailed research agenda for improving the NFA is established as a way of reaching consensus on priorities for implementing ecological footprint standards (Kitzes et al., 2009).

3.2.2. Energy footprint

Ferng's (2002) initiative highlights the importance of the energy footprint independent of the ecological footprint in energy scenario analysis by using an input–output analysis (IOA) based framework. Over the past years, an expanding list of researchers has chosen to concentrate exclusively on the topic of the energy footprint (e.g. Palmer, 1998; Stöglehner, 2003; Wiedmann, 2009a). It was previously introduced as a sub-indicator of the ecological footprint, representing the amount of forest area that would be required to absorb CO_2 emissions from fossil fuel combustion and electricity generation through the use of sequestration values for a world-average forest (Wackernagel and Rees, 1996). Depending on updated data obtained from the Intergovernmental Panel on Climate Change (IPCC, 2001), the calculation of the energy footprint has been revised with a fraction of approximately 30% of the total anthropogenic emissions for ocean uptake (Borucke et al., 2013; Monfreda et al., 2004). Recently, some researchers argue for a redefinition of the energy footprint as the sum of all area used to sequestrate CO_2 emissions from the consumption of non-food and non-feed energy (Čuček et al., 2012b; GFN, 2009).

3.2.3. Carbon footprint

The carbon footprint has become tremendously popular over the last few years, giving rise to a wide range of discussions in the scientific community. It is defined as the amount of CO_2-equivalent emissions caused directly and indirectly by an activity (Wiedmann and Minx, 2008), or as the total amount of greenhouse gas (GHG) emissions over the life cycle of a process or product (BSI, 2008). The usefulness of the carbon footprint differs from the energy footprint and has been justified in two respects: it takes into account non-CO_2 emissions (e.g. CH_4, N_2O) of which the global warming potentials (GWPs) are much higher than that of CO_2 (IPCC, 2007; Weidema et al., 2008), and the carbon footprint makes it easy to allocate the responsibility for global warming to consumers (Wiedmann and Minx, 2008; Wright et al., 2011). It is widely accepted that the life cycle assessment (LCA) is a useful tool for calculating the carbon footprint, especially at the product level (Wiedmann and Minx, 2008). Some standards such as the PAS 2050 (BSI, 2008) and ISO 14067 (Wiedmann, 2009b) have been or are being established on a life cycle basis.

3.2.4. Water footprint

The water footprint is another booming indicator that has gained worldwide popularity in recent years. It is defined as the cumulative virtual water content of all products and services consumed by individuals or communities within a given region (Hoekstra, 2009; Hoekstra and Hung, 2002). The real-water content of a product, in most cases, could be much less than the virtual-water content (Chapagain and Hoekstra, 2008). The water footprint can thus be termed in a way similar to that of the embodied energy, namely the "embodied water" (Chambers et al., 2000). Two principal methods have been applied to water footprint accounting: the bottom-up and top-down approaches (Feng et al., 2011; Hoekstra, 2009; Van Oel et al., 2009). The bottom-up approach belongs to process analysis using detailed descriptions of individual production processes and, conversely, the top-down approach resembles IOA which is an economic approach adopted in economic and environmental domains (Feng et al., 2011). The international water footprint standards are simultaneously under development by the Water Footprint Network (WFN) (Hoekstra et al., 2011) and the International Organization for Standardization (ISO 14046) (Ridoutt and Huang, 2012).

3.3. Comparison of selected footprints

Based on a review of original articles on footprint fundamentals and applications over the past two decades, here, we will examine the differences and similarities of the ecological, energy, carbon and water footprints by listing key issues in Table 2. Despite sharing the term "footprint" in their names, the four footprints differ in many aspects far more than the impacts addressed, such as conceptual roots, research stressors, footprint components, metric units, calculation methods, and so on. We will elaborate the key differences item by item.

3.3.1. Roots and stressors

a. The ecological footprint is built upon a tradition of seeking alternatives to the appropriated carrying capacity which is related to the maximum population size that can be supported by a given set of resources (Dietz and Neumayer, 2007; Ehrlich, 1982). It is intended to deal with the question of how much area of biologically productive space is required to produce consumed resources and to absorb generated waste.
b. The origin of the energy footprint can be traced back to a subset of the ecological footprint (Wackernagel and Rees, 1996) in reply to the question of how much forest area is required to absorb CO_2 emissions from energy consumption. The energy footprint, in many cases, makes up a dominant proportion of the entire amount of ecological footprint at a regional or global level (Kitzes et al., 2009).
c. The carbon footprint is rooted in the indicators of GWP which represents the quantities of GHGs that contribute to global warming when considering a specific time horizon such as 100 years (Høgevold, 2003; Wiedmann, 2009b). It is concerned with the question of how much CO_2-equivalent weight of the total GHG emissions is over the life cycle of products or activities.
d. The water footprint is derived from the concept of virtual water equal to the volume of freshwater used to produce a commodity (Allan, 1998; Hoekstra, 2009). It aims to address the question of how much volume of the cumulative virtual water is needed to provide products or activities.

3.3.2. Components and units

a. In ecological footprint accounting, six footprint components are distinguished in accordance with major land use types. All of these are built on six ecosystem services for human well-being: plant-based food production, livestock-based food production, fish-based food production, timber production, living space supply, and energy-related CO_2 absorption (Galli et al., 2012; Kitzes et al., 2009; Moore et al., 2012). Components are weighted with equivalence factors before being added up to the total. The ecological footprint, therefore, is a land-based, composite indicator (Wackernagel and Rees, 1996; Steen-Olsen et al., 2012). It is expressed in the common unit of global hectares (gha) that is equal to the hectares of land normalized to world average productivity of all biologically productive space within a given year (Galli et al., 2007).
b. The energy footprint can be classified into concrete components such as the fossil fuel footprint, the hydroelectricity footprint, and the nuclear footprint (Browne et al., 2009; Čuček et al., 2012b; Stöglehner, 2003), all of which are expressed as the area of forest that is necessary to compensate for human-induced CO_2 (Van den Bergh and Verbruggen, 1999). The unit of measurement can be gha or local hectares with a specific carbon sequestration estimate (Walsh et al., 2010).
c. The components of the carbon footprint include a variety of GHGs such as CO_2, CH_4, and N_2O. The use of GHG characterization factors as determined weightings dependent on the 100-year GWP has a broad base of acceptance (Ridoutt and Pfister, 2013)

Table 2
Main characteristics of the ecological, energy, carbon, and water footprints.

Item	Ecological footprint	Energy footprint	Carbon footprint	Water footprint
Conceptual roots	Carrying capacity	Ecological footprint	Global warming potential	Virtual water
Research stressors	Biologically productive land for supporting resources consumption	Forest for absorbing energy-related GHG emissions	GHG emissions from products or activities	Freshwater for supporting products or activities
Footprint components	Cropland, grassland, woodland, fishing ground, built-up land, carbon uptake land	Fossil fuel, hydroelectricity, nuclear, etc.	CO_2, CH_4, N_2O, etc.	Blue water, green water, grey water
Metric units	Area-based (gha, ha, etc.)	Area-based (gha, ha, etc.)	Mass-based (kg, t, etc.)	Volume-based (m^3, L, etc.)
Calculation methods	NFA, NFA-NPP, IOA, LCA, bottom-up, top-down, emergy, exergy, MEA	NFA, NFA-PLUM, IOA, bottom-up, top-down	IOA, LCA, hybrid approach	IOA, LCA, bottom-up, top-down
Data availability	High	Medium	Low	Low
Methodological standardization	Medium	Low	High	High
Weighting accuracy	Medium	Not applicable	High	Low
Resultant interpretation	High	High	Low	Medium
Geographical specification	Medium	Medium	Low	High
Global comparability	High	High	Low	Low
General applicability	High	Low	High	High

Notes: NPP – net primary productivity; MEA – millennium ecosystem assessment; PLUM – product land use matrix.

because the greater the GWP of a GHG, the more responsibility it should take on for increasing global temperatures. The metric is expressed in CO_2-equivalent mass units such as kilogram or ton, indicating the impact unit of time-integrated radiative forcing.

d. The water footprint consists of three components in volume-based units: the blue, green and grey water footprints. The blue and green footprints correspond to the demand for freshwater resources (from surface or ground water, and from rain, respectively), while the grey footprints refer to the waste assimilation by water and is defined as the volume of freshwater required to assimilate the load of pollutants based on the existing ambient water quality standards (Chapagain and Hoekstra, 2008; Hoekstra, 2009). Although Hoekstra (2009) has declared that no weighting is involved, equal weighting is also a form of weighting. It fails to distinguish the green, blue, and gray water components as they should have held different values for the environment (Hoekstra, 2009). The blue water's opportunity cost, for instance, is thought to be higher than the green water (Chapagain et al., 2006a).

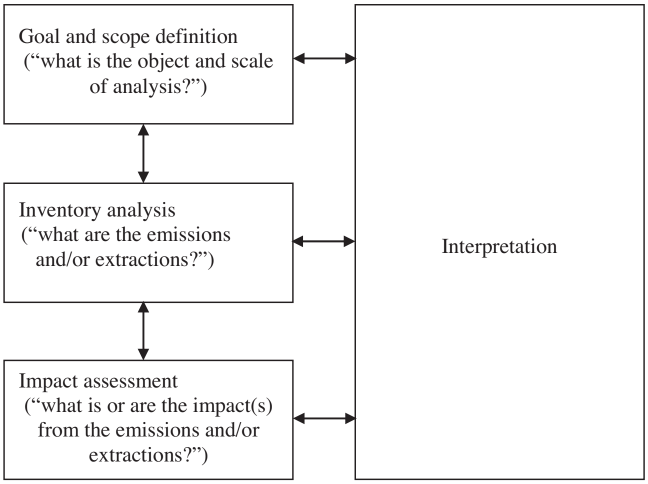

Fig. 2. Three phases of the implementation of an impact assessment in the framework of LCA.

3.3.3. *Methods and scales*

An important aspect to consider is that a footprint measures the impact of X on Y, where Y stands for land appropriation, climate change, virtual water, etc., and X stands for a product, an organization, a country, etc. In other words, the object and scale of study act as an important contributor to the methodological options of a given footprint. A full understanding of all of the possible methods for the four footprints on different scales is, therefore, needed.

Using the language of LCA, we may distinguish a phase of goal and scope definition where the object and scale ("X") are defined, a phase of inventory analysis where the emissions and/or resource extractions are determined, and a phase of impact assessment where the emissions and/or extractions are further modeled into impacts (on "Y"). Fig. 2 illustrates the ideas. Table 3 categorizes the literature into the two dimensions of object/scale ("X") and impact/footprint ("Y").

a. As noted above, the mainstream researchers of the ecological footprint place particular emphasis on the assessment at the national level, and modifications have been continuously supplemented to the NFA (Borucke et al., 2013; Wiedmann and Barrett, 2010). In addition to the typical NFA, several common tools for quantifying the ecological footprint at the macro-scale have been implemented including the NFA-NPP, IOA, MEA, emergy analysis, and exergy analysis. For instance, IOA can facilitate the calculation of a national ecological footprint of different categories of final demand (Tukker et al., 2009). A micro- or meso-scale ecological footprint often benefits from the component-based (bottom-up) or compound-based (top-down) approaches. Moreover, since LCA is more comprehensive in terms of coverage of impact categories but neglects the limits of renewable capacity supplied by the biosphere (i.e. biocapacity), studies have recommended to give priority to combining the ecological footprint and LCA in a complementary way so that more robust and detailed sustainability assessment could be achieved (Castellani and Sala, 2012; Huijbregts et al., 2008).

b. The NFA and its variation, NFA-PLUM, are the most common options for the organizational- or national-level energy footprint analysis. However, unlike the ecological footprint, many of the alternative approaches mentioned above are not available for the energy footprint. Moreover, from a methodological perspective, there is a great need to clarify which key features distinguish the energy footprint from the carbon footprint. It is our conviction that the most crucial difference between them is that the energy footprint takes a further step in translating the amount of CO_2 emissions into the amount of biologically productive land and

Table 3
Summary of approaches applied to the studies of ecological, energy, carbon, and water footprints from the literature.

Object/scale	Ecological footprint	Energy footprint	Carbon footprint	Water footprint
Product/food/energy	LCA (Huijbregts et al., 2008) Bottom-up approach (Simmons et al., 2000) Top-down approach (Mamouni Limnios et al., 2009)	Bottom-up approach (Šantek et al., 2010) Top-down approach (Stöglehner, 2003)	LCA (Carballo-Penela and Doménech, 2010) Hybrid approach (Virtanen et al., 2011)	LCA (Ridoutt and Pfister, 2010) Bottom-up approach (Chapagain et al., 2006b) Top-down approach (Van Oel et al., 2009)
Organization/sector/trade/building	IOA (Hubacek and Giljum, 2003) Bottom-up approach (Simmons et al., 2000) Top-down approach (Bastianoni et al., 2007) Emergy (Zhao et al., 2013)	IOA (Ferng, 2002) Top-down approach (Chen and Lin, 2008) NFA (Browne et al., 2009) NFA-PLUM (Wiedmann, 2009a)	IOA (Huang et al., 2009) LCA (Sanyé et al., 2012) Hybrid approach (Berners-Lee et al., 2011)	IOA (Steen-Olsen et al., 2012) Bottom-up approach (Van Oel et al., 2009) Top-down approach (Van Oel et al., 2009)
Region/nation/world	IOA (Lenzen et al., 2012) NFA (Wackernagel and Rees, 1996) NFA-NPP (Venetoulis and Talberth, 2008) MEA (Burkhard et al., 2012) Emergy (Zhao et al., 2005) Exergy (Chen and Chen, 2007)	NFA (Chen and Lin, 2008)	IOA (Hertwich and Peters, 2009)	IOA (Zhao et al., 2009) Bottom-up approach (Hoekstra and Mekonnen, 2012)

Note: Only literature focusing exclusively on the topic of energy footprint would be considered as a reference to the column of the energy footprint.

water required to absorb these emissions than does the carbon footprint (Fang et al., 2013).

c. Given the widespread acceptance of LCA in carbon footprinting, it has almost become the preferred method for measuring the product-level carbon footprint (Wiedmann and Minx, 2008). However, limitations hampering the application of LCA have been observed in terms of boundary settings and responsibility sharing among the organizational or national carbon footprints, with the particular argument that a full life-cycle perspective does not allow both producers and consumers to evaluate their footprints without double counting (Lenzen et al., 2007; Peters, 2010). Currently, there are a growing number of studies on hybrid approaches for companies or sectors, which combine the strength of both LCA and IOA in order to cover a broader scope of organizations and their activities (Heijungs and Suh, 2002).
d. In the water footprint analysis the bottom-up and top-down approaches both serve as major supporting tools. The former is accumulated item by item by multiplying all products and activities consumed by the respective water needs for those commodities. In some cases, it appears to be more reliable than the latter (Van Oel et al., 2009) which is, on the contrary, calculated as the total use of freshwater plus the gross virtual-water import minus the gross virtual-water export (Hoekstra, 2009), resembling the NFA of the ecological footprint. Furthermore, the NFA has been argued to be a special case of generalized physical input-output formulation (Kitzes et al., 2009). Therefore, it seems reasonable to make a deduction from a broad point of view that the NFA and IOA are designed in a similar way.

3.3.4. *Other characteristics*

a. A strength of the ecological footprint lies in its spatial dependence for easy interpretation as it translates the demand for biological resources and energy by the population into an easily interpretable area-based unit (Cranston and Hammond, 2012; Kitzes and Wackernagel, 2009). In addition, the ecological footprint benefits from its counterpart biocapacity, which is the ability of the Earth to supply the ecosystem services that humanity consumes (Borucke et al., 2013), as the comparison between the two metrics enables us to differentiate sustainability evaluation from the environmental impact assessment of a given activity (Castellani and Sala, 2012; Kates, 2001). The ecological footprint, however, has come under intense criticism for several reasons such as controversial hypotheses, a weak analytical basis, and an aggregate calculation system (e.g. Fiala, 2008; Kitzes et al., 2009; Van den Bergh and Grazi, 2010; Vogelsang, 2002).
b. In comparison with the ecological footprint, the usefulness of the energy footprint becomes apparent as it establishes a delicate connection between atmospheric carbon emissions and terrestrial carbon sinks. However, objections to the basic methodology never stop. A noticeable critique of its scientific robustness can be attributed to the failure to capture energy-related emissions other than CO_2 and to reduce the uncertainty in the estimation of carbon sequestration rate (Kitzes et al., 2009; Van den Bergh and Verbruggen, 1999; Venetoulis and Talberth, 2008), even though some of the concerns have been addressed through a series of modified models (e.g. De Benedetto and Klemeš, 2009; Kitzes et al., 2009; Lenzen and Murray, 2001).
c. The carbon footprint is booming with a much broader appeal than alternative indicators and LCA (Weidema et al., 2008). Nevertheless, criticisms toward the carbon footprint remain. A prominent one is the view expressed by some observers that the huge demand for detailed data compromises the quality of outcome, especially in those situations where extremely limited data for use at micro- or meso-scale accounts lead to underestimation (Chakraborty and Roy, 2013; De Benedetto and Klemeš, 2009). Another criticism is that the lack of consideration of carbon sequestration land runs the risk of disregarding the terrestrial feedback processes such as abrupt degradation of forest or changes in the distribution of vegetation and oceanic fluxes that further affect the global carbon cycle, which may have subsequent detrimental impacts on climate (Fang et al., 2013).
d. Freshwater is a highly site-specific resource cycling throughout the planet (Herva et al., 2011; Kitzes et al., 2009); it requires tracking down the origin of consumer products at the place of production (Hoekstra, 2009). As a consequence, the water footprint is unlikely to be as globally expressed as the ecological footprint but, rather, to be a geographically explicit indicator

that show not only the volume of water use but also the locations with emphasis on the distinction between internal and external water footprints (Hoekstra, 2009). On the other hand, the water footprint seems to be more vulnerable to data constraints than the ecological footprint.

4. Discussion

The proposed footprint family allows for a broader assessment of significant environmental impacts. In order to better understand its role in tracking human pressures on the planet, an evaluation of the footprint family will be conducted by testing the performance in crucial respects, and key priorities for further development will be suggested as well.

4.1. Evaluation of the footprint family

4.1.1. Data availability

In the case of cross-national databases, the ecological footprint accounts from more than 150 nations during 1961–2008 have been consistently released by the GFN with a separate column for the energy footprint (e.g. Borucke et al., 2013; Ewing et al., 2010; GFN, 2009). A database of the carbon footprint for 73 nations is available as well (Hertwich and Peters, 2009). There is also an average of the data of the water footprint for 140 nations between 1996 and 2005 (Hoekstra and Mekonnen, 2012). Recently, the advanced online database, Eureapa (2012), has been constructed based on the support of the Global Trade Analysis Project (GTAP) version 7, in which detailed datasets on the ecological, carbon, and water footprints of 27 European Union member states and additional 18 nations or regions with 57 sectors are all available for the base year of 2004.

In contrast to the well-documented data at the national level, data for the micro-scale products and the meso-scale organizations are quite limited. For instance, the access to the database of a company which comprises detailed statistics of resources used and wastes discharged within the defined boundary, in many cases, is not available (EC, 2013). Data availability has become a limiting factor in the extension at the sub-national level. A consequence is that potential applications of the footprint family would be restricted to the national level. Nevertheless, this is constrained by a lack of available dedicated personnel and financial resources rather than a lack of understanding or willingness to promote data collection and quality (Kitzes et al., 2009).

4.1.2. Coverage complementarity

Each of the four footprints is designed for addressing environmental issues with different emphases and, hence, is a complement to and not a substitute for others. The carbon and water footprints have been found to be able to benefit the ecological footprint by providing core information on natural capital use in relation to human consumption of the atmosphere and hydrosphere, respectively (Galli et al., 2012). For instance, the fishing component of the ecological footprint denotes the area of sea space required to sustain the harvested aquatic species, while the water footprint includes the volume of evaporated and polluted water associated with the activity of fishing and aquaculture (Borucke et al., 2013; Hoekstra, 2009). Thus, the ecological and water footprints can be seen as two complementary indicators in terms of fishing-related impact assessment. Another example is the combination of the carbon and water footprints which can be profitably implemented as a pair of single-issue indicators allowing for trade-offs without the risk of problem shifting both in the case of potable water distribution (Del Borghi et al., 2013) and in the case of fresh tomato production (Page et al., 2012).

However, significant double counting of the footprint family has been discerned in terms of carbon emissions and sequestration. A partial solution is to exclude the carbon uptake land from ecological footprint accounting (Galli et al., 2012; Steen-Olsen et al., 2012; Van den Bergh and Verbruggen, 1999). It is better to rename the rest of the ecological footprint as “land footprint” which accounts for the actual land and ocean exploited by humanity (Steen-Olsen et al., 2012; Weinzettel et al., 2013). This can be justified by two arguments. First, the carbon uptake land is hypothetical land that does not exist and thus conflicts with the actual appropriated land within the aggregate ecological footprint account (Hubacek and Giljum, 2003; Van den Bergh and Verbruggen, 1999). Second, the carbon uptake land is tightly tied to energy-related carbon emissions and sequestration which are already covered by the energy and carbon footprints (Fang et al., 2013; Steen-Olsen et al., 2012). Nevertheless, there is still a need to get rid of the overlap between the energy and carbon footprints. A potential approach for making the energy footprint completely independent of the carbon footprint will be presented in Section 4.2.1.

4.1.3. Methodological consistency

Of particular interest in evaluating the footprint family is to what extent the consistency between different footprint indicators has been maintained. From a methodological perspective, this is largely driven by two factors: standardization and harmonization. With respect to the progress of methodological standardization, several accounting standards underlying individual footprints already exist in two internationally standardized formats (Giljum et al., 2011): the normative format (e.g. ISO and PAS) and the descriptive format (e.g. GFN and WFN). The normative one like the ISO never aims to standardize accounting methods in detail, and there is not even common agreement on how to interpret some of the ISO requirements, so diverging approaches have occurred spontaneously (Guinee et al., 2010). The descriptive one contains numerous detailed regulations in which it seems much easier to build consensus concerning methodology, transparency, and communications but is constrained by weak enforcement. In addition, the methodology for the energy footprint is not yet as standardized and scientifically robust as the cases of the ecological, carbon, and water footprints (Galli et al., 2012); therefore, there is much room for improvement in future studies of the energy footprint.

Harmonized accounting of the footprint family on the national level is most likely achieved through a unified MRIO-based framework as a series of MRIO models have been successfully applied to the measurements of the land footprint (Weinzettel et al., 2013), the energy footprint (Wiedmann, 2009a), the carbon footprint (Hertwich and Peters, 2009), and the water footprint (Yu et al., 2010), as well as to the measurements of different sets of footprints (Galli et al., 2013; Lenzen et al., 2012; Moran et al., 2013; Steen-Olsen et al., 2012). The life-cycle, consumption-based perspective of the MRIO models make it easy to operationalize the footprint family concept without distracting from the issue of responsibility allocation which is too complicated to be thoroughly settled (Finnveden et al., 2009; Heijungs and Suh, 2002; Lenzen et al., 2007; Wiedmann, 2009a). We, therefore, consider that MRIO models would become a consensus approach for the national-level footprint family studies. More importantly, the ongoing development of MRIO models has been accompanied with the recognition that an updated version should be prepared in such a way that it allows more conceivable footprints to be incorporated (Galli et al., 2013).

In contrast, the methodological harmonization of the micro- or meso-scale footprint family is far from satisfactory. Apart from the low data availability, this can be partially attributed to the fact that consumer products are, in many cases, not compatible with the top-down IOA but rather appear to be compatible with the bottom-up LCA (Peters, 2010). Therefore, the proposal for a full LCA-based footprint family (Ridoutt and Pfister, 2013) would be feasible, though this probably pertains to the product level. An integration of certain existing methods such as hybrid approaches which take advantage of the alignment of both LCA and IOA could be a prospective solution to formulating the organizational-level footprint family. Yet, the likelihood of such a development is not available as no footprint other than the carbon footprint has been tested with a hybrid approach (Ewing et al., 2012).

4.1.4. *Policy relevance*

A remarkable advantage of the footprint family is that it offers policy makers an overall vision of the combined effects of various human pressures which then enables a deeper understanding of environmental complexity. In a policy context, the analysis of any single footprint should not be uncoupled from others as impact categories are so tightly linked that changing one may profoundly affect others in ways that people do not expect. The carbon footprint, for instance, has been found to be a poor representative of the environmental burden of products because problems will shift to other impact categories (like photochemical ozone or human toxicity) if reducing the carbon footprint is overemphasized to manufacturers (Laurent et al., 2012). That is, perhaps, why policy makers are insistent on a set of indicators rather than just a single one (Kitzes et al., 2009). Only the completeness of those indicators can allow us to examine whether an improvement in one category would lead to undesirable situations in other categories. Problem shifting, to some extent, could thus be avoided by using the footprint family.

Meanwhile, the discrepancy between the ecological footprint and the other three footprints becomes apparent when looking at their underlying hypotheses. From an ecological footprint perspective, any emissions of GHGs or use of water resources would be compulsively labeled with "unsustainability" (Fiala, 2008) as a clear recognition of sustainable limits relative to the energy, carbon, and water footprints is lacking in scientific advice for policy makers. In other words, the energy, carbon, and water footprints suffer from the critique that no distinction is made between sustainable and unsustainable activities, while the ecological footprint is criticized for its arbitrariness of assuming zero environmental capacity for carbon accumulation in the atmosphere and for pollutant concentration in the hydrosphere. This illustrates a very important point: without the reference to sustainable limits, the footprint family cannot be used to determine whether or not natural capital is being consumed in a sustainable way; it is only appropriate to measure the environmental impacts derived from natural capital appropriation by consumption of biological resources and water, GHG emissions, and discharge of the resulting waste (Fang et al., 2013). A further extension of the footprint family in addressing planetary boundaries will be delineated in Section 4.2.2.

4.2. *Needs for further development*

4.2.1. *Monitoring stock depletion*

The environmental implications of energy use not only affect the atmosphere where anthropogenic warming impacts have been sufficiently denoted using the carbon footprint or the alternatives—the GHG footprint (Hertwich and Peters, 2009) or the climate footprint (Huijbregts et al., 2010), but also affect the lithosphere where fossil fuel is an essential natural resource for humanity and contributes most to the stocks of natural capital maintained throughout the world. Unlike the renewable natural resources such as cropland or grassland, the consumption of fossil energy will undoubtedly result in a diminished stock of natural capital. From a strong sustainability perspective, all renewable flows of resources and ecosystem services could be sparingly consumed, but finite stocks should remain constant (e.g. Costanza and Daly, 1992; Niccolucci et al., 2009; Wackernagel and Rees, 1997). If stock depletion continues to grow a tipping point beyond which a tremendously huge accumulation of debt will never be paid back by natural capital flows, the Earth-system would ultimately collapse with disastrous consequences for human beings (Rockström et al., 2009; Wackernagel and Rees, 1997). Given this concern, it is desirable to find a way of reshaping the energy footprint to monitor the depletion of stocks associated with energy consumption within a given year. We argue that the footprint family will benefit from such a remodeling because it allows for simultaneous tracking of human pressures on four life-supporting compartments of the Earth: the biosphere, lithosphere, atmosphere, and hydrosphere. The major challenges are to calculate the cumulative energy demand for non-renewable stocks and to determine how much stock can be consumed until the global ecosystem breaks down.

4.2.2. *Setting sustainable limits*

The measurement of the biocapacity introduced by the ecological footprint practitioners is unique and important (Ewing et al., 2012); it allows the footprints to be comparable with the relative limits, representing the degree to which biophysical limits have been approached or exceeded (Costanza, 2000). With the aim to complement the footprint family with an integrated sustainability core, it is of great importance to identify and quantify sustainable limits for some other footprints as well. The reality is that seven out of nine Earth-system processes identified by Rockström et al. (2009) including land use change (land footprint), climate change (carbon footprint), freshwater use (water footprint), nitrogen cycle (nitrogen footprint), phosphorus cycle (phosphorus footprint), biodiversity loss (biodiversity footprint), and chemical pollution (chemical footprint), have been addressed through a variety of footprint indicators. In this sense, the combination of those footprints as an extended footprint family which would have sufficient spatial coverage to encompass the majority of Earth-system processes may serve as a starting point for demarcating planetary boundaries. Given the gaps in current knowledge about the complexity of Earth-system, determining critical values for each of the planetary boundaries has to involve normative or even subjective judgments (Lewis, 2012; Rockström et al., 2009). Thus the major constraint on setting sustainable limits for a footprint family is that it is almost unlikely to be able to present reasonable and accurate estimates that can be consistently validated by the scientific community.

5. Conclusions

This paper provides an overview of a new footprint family which is designed in such a way that some significant environmental impacts associated with human activities can be measured through a set of selected footprint indicators. The ecological, energy, carbon, and water footprints involved in the proposed footprint family can be regarded as complementary to each other as each of them focuses on different aspects of environmental issues. The footprint family is found to be able to capture a broad spectrum of sustainability issues in relation to natural resource use and waste discharge, and to provide policy makers with a more complete picture of environmental complexity. This study shows that data for the footprint family is already available on the national level in which harmonized accounting is likely to be achieved through a unified MRIO-based framework. Nevertheless, the footprint family still suffers from limitations. Neither the data availability nor the methodological consistency has been satisfactory for products or organizations. Another weakness is due to the significant double counting that exists in terms of energy-related carbon emissions and sequestration.

Our discussion comprises a sequence of suggestions. First, the carbon uptake land is supposed to be disaggregated from the ecological footprint, and it is better to rename the remaining as "land footprint" which addresses the actual land appropriation by humanity. Second, data availability is a limiting factor for the micro- and meso-scale footprint family studies and thus deserves attention in efforts to improve data accessibility and reliability. Third, a full LCA could be appropriate for the footprint family at the product level while the hybrid approach might be a prospective solution to the organizational-level studies. Fourth, the footprint family can currently be used for assessing some relevant environmental impacts but not for evaluating environmental sustainability. To achieve a more rigorous footprint family, two priorities for further development are provided. One is to reshape the energy footprint to monitor the depletion of energy stocks. The other is to identify sustainable limits for a variety of footprints in order to complement the footprint family with a more comprehensive integrated sustainability core.

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