Ecological Indicators 16 (2012) 100–112

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Integrating Ecological, Carbon and Water footprint into a "Footprint Family" of indicators: Definition and role in tracking human pressure on the planet

Alessandro Galli[a,*], Thomas Wiedmann[b], Ertug Ercin[c], Doris Knoblauch[d], Brad Ewing[e], Stefan Giljum[f]

[a] Global Footprint Network, 312 Clay Street, Oakland, CA 94607-3510 USA
[b] CSIRO Ecosystem Sciences, Black Mountain, Canberra, ACT 2601, Australia
[c] University of Twente, P.O. Box 177, 7500 AE Enschede, The Netherlands
[d] Ecologic Institute, Pfalzburger Strasse 43/44, D-10717 Berlin, Germany
[e] University of California, Davis, USA
[f] Sustainable Europe Research Institute (SERI), Garnisongasse 7/17, Wien, A-1090, Austria

ARTICLE INFO

Article history:
Received 18 October 2010
Received in revised form 19 May 2011
Accepted 15 June 2011

Keywords:
Footprint Family
Ecological Footprint
Water Footprint
Carbon Footprint
Human impact assessment
Integrated approach
Policy role

ABSTRACT

In recent years, attempts have been made to develop an integrated Footprint approach for the assessment of the environmental impacts of production and consumption. In this paper, we provide for the first time a definition of the "Footprint Family" as a suite of indicators to track human pressure on the planet and under different angles. This work has been developed under the 7th Framework Programme in the European Commission (EC) funded One Planet Economy Network: Europe (OPEN:EU) project. It builds on the premise that no single indicator per se is able to comprehensively monitor human impact on the environment, but indicators rather need to be used and interpreted jointly. A description of the research question, rationale and methodology of the Ecological, Carbon and Water Footprint is first provided. Similarities and differences among the three indicators are then highlighted to show how these indicators overlap, interact, and complement each other. The paper concludes by defining the "Footprint Family" of indicators and outlining its appropriate policy use for the European Union (EU). We believe this paper can be of high interest for both policy makers and researchers in the field of ecological indicators, as it brings clarity on most of the misconceptions and misunderstanding around Footprint indicators, their accounting frameworks, messages, and range of application.

1. Introduction

1.1. Global environmental changes: an overview

In the last four decades, countries around the world have experienced economic growth, poverty reduction and improved welfare (UNDP, 2006; UNEP, 2007). These changes have been reached at the expense of the planet's ecosystem preconditions and ability to sustain life (Goudie, 1981; Haberl, 2006; Nelson et al., 2006; Rockström et al., 2009). Over the last century, the world population has quadrupled and global resource consumption and waste emissions have grown to a point where humanity now consumes at a faster pace than the Earth can regenerate (Haberl et al., 2007; Hoekstra, 2009; Wackernagel et al., 2002; WWF, 2010).

Forests, particularly in tropical zones, are cut faster than they can regrow (130,000 km^2 of forest have been destroyed per year for the last 15 years) and fishes are caught faster than they can restock (15% of ocean stocks were depleted in the same period) (UNEP, 2007). World average per capita food and services consumption has grown during the last four decades (Turner, 2008); global extraction of natural resources (e.g., biomass, fossil fuels, metal ores, and other minerals) has increased by nearly 45% in the last 25 years (Behrens et al., 2007; Giljum et al., 2009a; Krausmann et al., 2009). Many countries in arid and semi-arid regions of the world (e.g., Central and West Asia, North Africa) are already close to or below the threshold for water scarcity of 1000 m^3 $capita^{-1}$ $year^{-1}$ (Falkenmark, 1989). Greenhouse gas (GHG) emissions are accumulating in the atmosphere (IPCC, 2007a) causing climatic changes and potential negative feedback on the health of ecosystems (Butchart et al., 2010; Haberl, 2006; UNEP, 2007).

The distribution of human-induced pressures is uneven in both its nature (Behrens et al., 2007; Haberl, 2006; Krausmann et al., 2009) and geographic location (Erb et al., 2009; Foley et al., 2005; Giljum et al., 2009a; Haberl et al., 2007; Halpern et al., 2008; Hertwich and Peters, 2009; Hoekstra and Chapagain, 2007; Kitzes et al., 2008a; Niccolucci et al., this issue; Ramankutty and Foley, 1999; Ramankutty et al., 2002; Sutton et al., this issue). On a per capita basis, people in high income countries consume more resources than those in lower income countries. The transition from biomass-driven (agricultural) to fossil-fuel-driven (industrial) soci-

* Corresponding author. Tel.: +1 510 839 8879x310; fax: +1 510 251 2410.
E-mail address: alessandro@footprintnetwork.org (A. Galli).

1470-160X/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecolind.2011.06.017

eties experienced by high income countries (Haberl, 2006; Galli et al., 2011a) has determined a shift in the ecosystem compartments that are now under the highest human-induced pressure.

As scenarios illustrate, these trends will likely continue in the future if measures are not taken. In a business-as-usual scenario, global extraction of natural resources could further grow by more than 50% by 2030 compared to today's situation (Lutz and Giljum, 2009), and humanity's demand on ecological assets (in Ecological Footprint terms) could equal two Earths worth of resources slightly after 2030 (Moore et al., this issue). Up to two-thirds of the world population could experience water scarcity over the next few decades (Alcamo et al., 2000; Vörösmarty et al., 2000) and approximately one billion people could face absolute water scarcity (less than 500 m^3 $capita^{-1}$ $year^{-1}$) by 2025 (Rosegrant et al., 2002).

Empirical measurements have thus to be sought to understand the driving forces behind these impacts and find ways to reduce them while maintaining economic and societal well-being. The EC funded One Planet Economy Network: Europe (OPEN:EU) project, under which this work has been performed, originates from the willingness to enable policy makers to address the objectives of the EU Sustainable Development Strategy (SDS) and other policy strategies to help transform the EU into a One Planet Economy by 2050 (http://www.oneplaneteconomynetwork.org/index.html).

1.2. The need for a set of indicators

Managing the planet's ecological assets is becoming a central issue for decision makers around the world (Best et al., 2008). Integrated ecosystem approaches can potentially best inform decision makers as they enable tackling multiple issues concurrently and help avoid additional costs and/or inadvertently undoing progress in one sector by not accounting for direct and indirect implications of actions in other sectors (Robinson et al., 2006; Turner, 2008). The way human activities are linked to each other and affect different compartments of the planet has to be understood (Vörösmarty et al., 2000; Weisz and Lucht, 2009).

Climate change, for example, is currently seen as the most impending environmental issue deterring societies from sustainability. Unfortunately, in the search for sustainability, decision makers have approached sustainable development through the climate change lens (Robinson et al., 2006), with a smaller focus upon other impacts caused by humanity. Looking at carbon in isolation – rather than a symptom of humanity's overall metabolism of resources – has made us blind to other dangers. The world's appetite for water, food, timber, marine, and many other resources is also relevant with respect to resource limits (Ewing et al., 2010; Fischer-Kowalski and Haberl, 2007; Giljum et al., 2009b; Krausmann et al., 2009; WWF, 2010).

1.3. The need for a consumer approach

If we lived in a world where countries produced and consumed all goods and services within their borders, the distinction between consumption-based and production-based accounting would be unnecessary. But we live in a highly globalized world, where economies of scale and comparative advantage in many areas exist, rendering trade and commerce highly valuable and "responsibility" over impacts much more complex. For instance, given the existing global environmental policy framework (e.g., Kyoto protocol) holding producers rather than final consumers responsible for human impact, a perverse incentive exists for industrialized countries to outsource high-impacting activities to transition economies, where such activities are usually carried out in a cheaper but less eco-efficient way. This is likely to cause an increase in the overall environmental pressure associated with consumption activities as countries tend to import environmentally-inefficient goods and services to sustain their consumption patterns.

After years of debate (i.e., Bastianoni et al., 2004; Lenzen et al., 2007; Peters, 2008), consumption-based accounting (CBA) is becoming increasingly relevant as it provides several opportunities for policy and decision making processes. As highlighted by Wiedmann (2009), CBA is useful in complementing territorial-based approaches by including all driving forces for demands on ecological assets associated with consumption activities. CBA can provide complementary information for the formulation of international environmental policy frameworks, where the participation of developing countries could be favored through the alleviation of competitiveness concerns, thus facilitating international cooperation among developing and developed countries. Finally, CBA can be used to monitor decoupling and design strategies on sustainable consumption and production policies at the national, regional and local levels.

Ecological, Carbon and Water Footprints are able to complement traditional analyses of human demand by coupling producer and consumer perspectives. These indicators present a quantifiable and rational basis on which to begin discussions and develop answers regarding the efficiency of production processes, the limits of resource consumption, the international distribution of the world's natural resources, and how to address the sustainability of the use of ecological assets across the globe (Senbel et al., 2003).

By bringing together Ecological, Carbon and Water Footprints into a single conceptual framework, the aim of this paper is to provide analysts and decision makers with a robust and ready-to-use suite of indicators enabling them to take the first step towards a multidisciplinary sustainability assessment; however, it is not the scope of this paper to create a new indicator. While the analysis performed in this study may highlight areas for potential modifications and improvements of the selected indicators (see Section 4.4), implementing such modifications goes beyond the scope of the OPEN:EU project and this paper.

The remainder of the paper is thus structured as follow: Section 2 provides a description of the 'traditional' Ecological, Carbon and Water Footprint methodologies; Section 3 summarizes their complementary and overlapping properties and defines the "Footprint Family" suite of indicators as in use in the OPEN:EU project; Section 4 gives insight on the potential role of the Footprint Family in the EU policy context and provides information on the limitations and potential future improvements. Final remarks are provided in the conclusion section.

2. Methods

Three indicators have been selected to be included in the Footprint Family for use in the OPEN:EU project: Ecological, Carbon and Water Footprint. Beyond the similarity in name, these three methods were selected because of their scope and research question.

2.1. Ecological Footprint

The Ecological Footprint is a resource and emission[1] accounting tool designed to track human demand on the biosphere's regenerative capacity (Wackernagel et al., 1999a, 2002). It documents both direct and indirect human demands for renewable resource production and CO_2 assimilation and compares them with the planet's ecological assets (biocapacity) (Monfreda et al., 2004; Wackernagel et al., 1999b). In doing so, Ecological Footprint and biocapacity

[1] CO_2 is the only greenhouse gas accounted by the Ecological Footprint method.

accounting take into account both the sustainability principles identified by Daly (1990).

By tracking a wide range of human activities, the Ecological Footprint monitors the combined impact of anthropogenic pressures that are more typically evaluated independently (CO_2 emissions, fish consumption, land-use change, etc.) and can thus be used to understand the environmental consequences of the pressures humans place on the biosphere and its composing ecosystems. The Ecological Footprint can be applied at scales ranging from single products, to cities and regions, to countries and the world as a whole (Ewing et al., 2010).

Six key ecosystem services widely demanded by the human economy are tracked and associated with a type of bioproductive land: plant-based food and fiber products (cropland); animal-based food and other animal products (cropland and grazing land); fish-based food products (fishing grounds); timber and other forest products (forest); absorption of fossil carbon dioxide emissions (carbon uptake land[2]); and the provision of physical space for shelter and other infrastructure (built-up area).

Ecological Footprint and biocapacity values are used to measure one key aspect of sustainability: the human appropriation of the Earth's regenerative capacity. They analyze the human predicament from this distinct angle, under the assumption that the Earth's regenerative capacity will likely be one of the limiting factors for the human economy if human demand continues to overuse beyond what the biosphere can renew. Further aspects of the Ecological Footprint can be found in Kitzes et al. (2009) while a review of existing methods have recently been presented by Wiedmann and Barrett (2010). An interesting discussion on the Ecological Footprint rationale is included in Bastianoni et al. (this issue).

The Ecological Footprint and biocapacity are resource flow measures. However, rather than being expressed in tonnes per year, each flow is expressed in units of area, annually necessary to provide (or regenerate) the respective resource flow. This reflects the fact that many basic ecosystem services and ecological resources are provided by surfaces where photosynthesis takes place. These surfaces are limited by physical and planetary constraints and the use of an area better communicates the existence of physical limits to the growth of human economies (GFN, 2010; Monfreda et al., 2004).

As bioproductivity differs between various land use types and countries, Ecological Footprint and biocapacity values are usually expressed in units of world average bioproductive area, namely global hectares – gha (Galli et al., 2007; Monfreda et al., 2004). Yield factors and equivalence factors are the two 'scaling factors' used to express results in terms of global hectares (Galli et al., 2007; Monfreda et al., 2004), thus allowing comparisons between various types of bioproductive land and various countries' Ecological Footprint and/or biocapacity.

2.2. Carbon Footprint

The Carbon Footprint measures the total amount of GHG emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product.[3] This includes activities of individuals, populations, governments, companies, organizations, processes, industry sectors, etc. In any case, all direct (on-site, internal) and indirect emissions (off-site, external, embodied, upstream, and downstream) need to be taken into account. More specific aspects such as which GHGs are included and how double-counting is addressed can vary (Wiedmann and Minx, 2008).

When applied to a nation, the Carbon Footprint relates to consumption of goods and services by households, governments, and other 'final demand' such as capital investment. It also relates to the GHG emissions embodied in trade: the Carbon Footprint of a nation is the sum of all emissions related to the nation's consumption, including imports and excluding exports. As such, the consumption-based perspective of the Carbon Footprint complements the production-based approach taken by national greenhouse gas inventories, such as those considered by the Kyoto Protocol. Consumption-based carbon footprinting could encourage and facilitate international cooperation between developing and developed countries; it could be used to make consumers aware of the GHG emissions from their life-style and raise awareness of indirect emissions in governments and businesses.

Despite its name, the Carbon Footprint is not expressed in terms of area. The total amount of greenhouse gases is simply measured in mass units (kg, t, etc.) and no conversion to an area unit (ha, m^2, km^2, etc.) takes place. Any conversion into a land area would have to be based on a variety of assumptions that would increase the uncertainties and errors associated with a particular Carbon Footprint estimate.

When only CO_2 is included, the unit is kg CO_2; if other GHGs are included the unit is kg CO_2-e, expressing the mass of CO_2-equivalents. Those are calculated by multiplying the actual mass of a gas with the global warming potential factor for this particular gas, making the global warming effects of different GHGs comparable and additive. In the OPEN:EU project, the six greenhouse gases identified by the Kyoto Protocol are included in the analysis: CO_2, CH_4, N_2O, HFC, PFC, and SF_6.

2.3. Water Footprint

The Water Footprint concept was introduced in response to the need for a consumption-based indicator of freshwater use (Hoekstra, 2003). It is closely linked to the virtual water concept (Allan, 1998) as it accounts for the appropriation of natural capital in terms of the water volumes required for human consumption (Hoekstra, 2009).

The Water Footprint looks at both direct and indirect water use of a consumer or producer. Three key water components are tracked in its calculation: the blue Water Footprint refers to consumption of surface and ground water; the green Water Footprint refers to consumption of rainwater stored in the soil as soil moisture; the grey Water Footprint refers to pollution and is defined as the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra, 2009).

Water Footprint can be calculated for a particular product, for any well-defined group of consumers (e.g., an individual, city, province, state, or nation) or producers (e.g., a public organization, private enterprise, or economic sector) and it is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business (Hoekstra and Chapagain, 2008). The first assessment of Water Footprints of countries was carried out by Hoekstra and Hung (2002). A more extended assessment was done by Chapagain and Hoekstra (2004).

The Water Footprint concept aims primarily at illustrating the hidden links between human consumption and water use and between global trade and water resources management. This concept has been brought into water management science in order to show the importance of human consumption and global dimensions in good water governance (Hoekstra, 2009).

[2] It should be noted that the demand for the biosphere's carbon uptake capacity is usually also referred to as "carbon footprint", though this should not be confused with the "Carbon Footprint" methodology described in Section 2.2.

[3] Products include goods and services.

Water use is measured through the Water Footprint method in terms of water volumes consumed (evaporated or incorporated into the product) and polluted per unit of time. Depending on the level of detail that one aims to provide, it can be expressed per day, month, or year (Hoekstra, 2009).

3. Discussion

3.1. Testing and comparing Footprint indicators

According to van den Bergh and Verbruggen (1999), the search for operational indicators should be guided by a number of specific criteria that indicators or set of indicators should meet. This has been a guiding principle in analyzing the Ecological, Carbon and Water Footprint, which have been tested against criteria such as scientific robustness, presence of a clear research question, policy usefulness, temporal and spatial coverage, etc. (see also Galli et al., 2011b). Similarities and differences among the three indicators have been highlighted to show how the indicators overlap, interact, and complement each other.

As any indicator is, by definition, a simplification of a much more complex reality, sets of indicators such as the Footprint Family or alternative "baskets of indicators" could be more informative for policy makers (e.g., Best et al., 2008); however, their range of application as well as usefulness in tracking the functioning of a larger scope of the Earth's ecosystems has first to be tested before they can be actually adopted (Table 1).

All three indicators were found able to represent the environmental consequences of human activities and complementary in assessing human pressure on the planet from a consumer-based angle; however, they are built upon different research questions and tell different stories.

The Ecological Footprint focuses on the aggregate demand that resource consumption places on the planet's ecological assets; thus recognizing the existence of limits to our growth and trying to measure them. The Water Footprint focuses on the human appropriation of natural capital in terms of fresh water volumes required for human consumption; it is primarily intended to illustrate the hidden links between consumption activities and water use. The Carbon Footprint focuses on the total amount of GHGs released due to resource-consumption activities and provides a better understanding of humans' contribution to GHG emissions.

All three indicators are characterized by a wide spatial coverage and scale of applicability: they can all be applied to single products, cities, regions, nations and up to the whole planet. In terms of time coverage, the Ecological Footprint was found to be the most comprehensive as it covers a 1961–2007 time period, while values exist for the year 2001 and an averaged 1996–2005 period only for the Carbon and Water Footprint, respectively.

The three indicators are able to track both direct and indirect human demands, thus favoring a clear understanding of the 'hidden/invisible' human-induced sources of pressure. However, only the Ecological and Water Footprint were found able to account for both the source (resource production) and sink (waste assimilation) capacity of the planet. The Ecological Footprint was then found to be the sole indicator able to provide a clear ecological benchmark (biocapacity) to test human pressure against. Setting a benchmark for the Carbon Footprint indicator is currently being considered in the OPEN:EU project.

A significant overlap exists between Ecological and Carbon Footprint as human-induced CO_2 emissions are tracked by both methodologies. However, both methodologies go beyond the sole CO_2 investigation[4] as the Carbon Footprint also tracks the release of additional GHGs (usually CO_2, CH_4, N_2O, HFC, PFC, and SF_6) and the Ecological Footprint expands its area of investigation by looking at human demand for food, fibers, wood products, etc.

For what concern Ecological and Water Footprint, a partial overlap exists between these two indicators. As recognized by Kitzes et al. (2009), freshwater is a natural resource cycling through the biosphere, whose availability or scarcity influence the regenerative capacity (biocapacity) of the planet. However, water itself is not a creation of the biosphere for which the planet has a regenerative capacity. As such the direct Ecological Footprint of a given quantity of water cannot be calculated, though it is possible to measure the Ecological Footprint embedded in the provisioning of water, including waste water treatment (Lenzen et al., 2003). Conversely, direct and indirect freshwater requirements are clearly tracked by the Water Footprint indicator. The combined use of Ecological and Water Footprint within the Footprint Family suite of indicators is thus deemed to be the best approach to develop a multi-criteria decision making process and provide information to back up water policies.

3.2. Definition of the Footprint Family

Recently several attempts have been made at bringing together Footprint approaches for the assessment of the environmental impact of productions (Giljum et al., 2011; Niccolucci et al., 2010; Patrizi, 2009). However, the OPEN:EU project is to our knowledge the first attempt at clearly providing a definition to the Footprint Family of indicators in its wider range of applicability. This is also one of the first attempts at grouping consumer-based indicators into a single suite of indicators.

The Footprint Family is here defined as a set of indicators – characterized by a consumption – based perspective – able to track human pressure on the surrounding environment, where pressure is defined as appropriation of biological natural resources and CO_2 uptake, emission of GHGs, and consumption and pollution of global freshwater resources. Three key ecosystem compartments are monitored, namely the *biosphere*, *atmosphere*, and *hydrosphere* through the Ecological, Carbon and Water Footprint, respectively.

The Footprint Family has a wide range of research and policy applications as it can be employed at scales ranging from a single product, a process, a sector, up to individual, cities, nations, and the whole world. The Footprint Family provides an answer to three specific research questions and helps to more comprehensively monitor the environmental pillar of sustainability. However, it is not yet a full measure of sustainability as several environmental, economic and social issues are not tracked (see Section 4.4).

3.3. The need for a streamlined ecological-economic modelling framework

Although grouped under a single conceptual framework – the Footprint Family – each of the three indicators is currently characterized by its own calculation methodology and accounting framework as reported in the scientific literature: Carbon Footprint accounts (Hertwich and Peters, 2009) utilize a Multi-Regional Input–Output (MRIO) model to allocate emissions to consumption; conversely Water and Ecological Footprint have been historically calculated using process-based LCA data and physical quantities of traded goods (Hoekstra et al., 2009; Kitzes et al., 2008b).

[4] It should be noted that the Carbon Footprint only captures the demand (or emission) side of the equation, not how much the planet can accommodate (the ecological supply side or its absorptive capacity).

Table 1
Indicators' testing phase: outcomes.

	ECOLOGICAL FOOTPRINT	CARBON FOOTPRINT	WATER FOOTPRINT
RESEARCH QUESTION	The amount of the biosphere's regenerative capacity that is directly and indirectly (i.e. embodied in trade) used by humans (namely Ecological Footprint) compared with how much is available (namely biocapacity), at both local and global scale.	The total amount of GHG emissions (CO_2, CH_4, N_2O, HFC, PFC, and SF_6) that are directly and indirectly caused by human activities or accumulated over the life stages of products.	The human appropriation of the volume of freshwater required to support human consumption.
MAIN MESSAGE	To promote recognition of ecological limits and safeguard the ecosystems' life-supporting services enabling the biosphere to support mankind in the long term.	The consumption-based perspective of the Carbon Footprint complements the production-based accounting approach taken by national GHG inventories (e.g., those considered by the Kyoto Protocol).	The Water Footprint concept is primarily intended to illustrate the hidden links between human consumption and water use and between global trade and water resources management.
DATA AND SOURCES	• Data on local production, import and export for agricultural, forestry and fisheries products (FAOSTAT, UN Comtrade); • Land use data (FAOSTAT, etc); • Local and trade-embedded CO_2 emissions (IEA and others); and • Land yield (FAOSTAT) and potential crop productivity (provided by the FAO GAEZ model) – this data is needed to express results in units of global hectares.	• National economic accounts (supply, use, input-output tables); • International trade statistics (UN, OECD, GTAP and others); and • Environmental accounts data on GHG emissions (IEA, GTAP, and others).	• Data on population (World Bank); • Data on arable lands (FAO) and total renewable water resources and water withdrawals (FAO); • Data on international trade in agricultural (PC-TAS) and industrial products (WTO); and • Local data on various parameters such as climate, cropping patterns, soil, irrigation, leaching, water quality, pesticides and fertilizers rates, etc.
UNIT OF MEASUREMENT	• Global hectares (gha) of bioproductive land. Gha is not a measure of area but rather of the ecological production associated with an area; and • Results can also be expressed in actual physical hectares.	• Kg CO_2 when only CO_2 is included or kg CO_2-equivalent when other GHGs are included as well; and • No conversion to an area unit takes place to avoid assumptions and uncertainties.	• Water volume per unit of time (usually $m^3\ yr^{-1}$) for the Water Footprint of processes; • $m^3\ ton^{-1}$ or liter kg^{-1} for the Water Footprint of products; and • Water volume per unit of time for the Water Footprint of a geographical area.

Table 1
(*Continued*).

	ECOLOGICAL FOOTPRINT	CARBON FOOTPRINT	WATER FOOTPRINT
INDICATOR COVERAGE	• Temporally explicit and multi-dimensional indicator that can be applied to single products, cities, regions, nations and the whole biosphere; • Data are available for approximately 240 nations for the period 1961-2007; however, data for only about 150 nations are consistently published (Ewing et al., 2010); • Documents both direct and indirect human demands for both the **source** (resource production) and the **sink** (carbon uptake) capacity of the biosphere; • Provides a measure of both human **demand** and nature **supply**; • Provides a clear benchmark; and • It has a consumption-based point of view and thus considers trade.	• Multi-dimensional indicator that can be applied to products, processes, companies, industry sectors, individuals, governments, populations, etc.; • 113 nations and world regions for the year 2004 when using the GTAP7 database (Wiedmann, 2009); • Documents all direct and indirect GHGs emissions due to use of resources and products (**source**); • Measures the '**demand**' side only, in terms of the amount of GHGs emitted; and • It has a consumption-based point of view and thus considers trade.	• Geographically explicit and multi-dimensional indicator: it can be calculated for products, public organizations, economic sectors, individuals, cities and up to nations; • 140 nations for the period 1996-2005 are tracked (Mekonnen and Hoekstra, 2010); • Documents both the direct and indirect use of natural capital as a **source** (demand on blue and green waters) and as a **sink** (grey water to dilute pollution); • Measures the '**demand**' side only, in terms of freshwater consumed (by sources) and polluted (by type of pollution) by human activities; • No benchmark is provided; and • It has a consumption-based approach and considers trade.
POLICY USEFULNESS	• Measures 'overshoot' and identifies the pressures that humanity is placing to various ecosystem services; • Monitors societies' progresses towards minimum sustainability criteria (demand ≤ supply); • Monitor the effectiveness of established resource use and resource efficiency policies; • Allows analyzing the consequences of using alternative energies; • Communicate environmental impacts of different life-styles to the overall public; • Track pressure on biodiversity; and • Illustrates the unequal distribution of resource use and availability.	• Offers an alternative angle for international policy on climate change as it complements the territorial-based approach used by the UNFCCC; • Offers a better understanding of countries' responsibility and could facilitate international cooperation and partnerships between developing and developed countries; • Can help design an international harmonized price for greenhouse gas emissions; and • Illustrates the unequal distribution of resource use.	• Gives a new & global dimension to the concept of water management & governance; • Offers nations a better understanding of their dependency on foreign water resources; • Offers river basin authorities info on the extent to which scarce water resources are allocated to low-value export crops; • Offers companies a way to monitor their dependence on scarce water resources alongside their supply-chain; and • Illustrates the unequal distribution of resource use.

Table 1
(*Continued*).

	ECOLOGICAL FOOTPRINT	CARBON FOOTPRINT	WATER FOOTPRINT
STRENGTHS	• Allows benchmarking human demand for renewable resources and carbon uptake capacity with nature supply and determining clear targets. • Provides an aggregated assessment of multiple anthropogenic pressures; and • Easy to communicate and understand with a strong conservation message.	• Allows for a comprehensive assessment of human contribution to GHG emissions; and • Consistent with standards of economic and environmental accounting. • Consistent emissions data available for the majority of countries.	• Represents the spatial distribution of a nation's water "demand"; • Expands traditional measures of water withdrawal (green and grey waters also included); and • Visualizes the link between (local) consumption and (global) appropriation of freshwater. Integrates water use and pollution over the production chain.
WEAKNESSES	• Cannot cover all aspects of sustainability, neither all environmental concerns, especially those for which no regenerative capacity exists (including abiotic resources); • Shows pressures that could lead to degradation of natural capital (e.g. reduced quality of land or reduced biodiversity), but does not predict this degradation; and • Not geographically explicit. • Some underlying assumptions are controversial, though documented	• Cannot track the full palette of human demands on the environment • Additional impact assessment models are needed to analyze the impact of climate change at both national and sub-national levels; • Efforts needed to set up and update a system of MRIO tables and related environmental extensions; and	• Only tracks human demand on freshwater; • It relies on local data frequently unavailable and/or hard to collect. It suffers from possible truncation errors; • No uncertainty studies are available, though uncertainty can be significant; and • Grey water calculation heavily relies on assumptions and estimations.
COMPLEMENTARY PROPERTIES IN THE FOOTPRINT FAMILY	• Uses a consumer-based approach to track human pressures on the planet in terms of the aggregate demand that resource-consumption and CO_2 emissions places on the ecological assets (impact on *biosphere*).	• Uses a consumer-based approach to track human pressures on the planet in terms of total GHG emissions and human contribution to climate change (impact on *atmosphere*).	• Uses a consumer-based approach to track human pressures on the planet in terms of the water volumes required for human consumption (impact on *hydrosphere*).

Bringing Ecological, Carbon and Water Footprint together under a single streamlined ecological-economic modelling framework would strengthen the robustness and consistency of the Footprint Family concept as this would enable an inter-industry analysis of the linkages across multiple economies as well as a better assessment of the trade-offs among the three indicators. To this end, an MRIO-Footprint model has been developed by the OPEN:EU project (Weinzettel et al., 2011; Hawkins et al., forthcoming).

However, this integration process conveys both pros and cons. While the integration of environmental and economic accounts is extremely valuable, approximations are required as part of the calculation to utilize economic flows as a proxy for the physical flows. Moreover, the use of Input–Output tables with Footprint indicators causes a decreased time coverage (as MRIO models usually refer to a single year only) and resolution (because of the shift from detailed product-level to aggregated sectoral-level assessments). The benefit of a purely physical flow accounting approach – where economic data is not introduced into the models – is that the product resolution is much higher and these accounts track the physical flows directly. However, the weakness of this approach is that physical flow datasets are less prevalent and developed than the economic flows related to the same products and the physical flow data sets only track goods, excluding services. These physical flow accounts also do not completely link with the supply chain or the economic activities that are driving the resource or waste flows (Hawkins et al., forthcoming).

4. The role of the Footprint Family in the EU Policy Context

4.1. Resource use trends at EU level

Home to 11% of the world population, Europe's demand on the biological capacities of the planet has risen by more than 70% since 1961 to a global share of 19% in 2007 (Ewing et al., 2010; WWF, 2010).

Inhabitants of Europe have per capita resource consumption levels around 3–5 times higher than those of developing countries (Giljum et al., 2009a; WWF, 2010). While extraction of natural resources has stabilized in Europe over the past 20 years, imports of raw materials and products have significantly increased (Dittrich, 2009; Weisz et al., 2006).

GHG emissions (in CO_2-equivalents) of average EU-27 citizens have been decreasing in the past years due to efforts to decrease domestic emissions (EEA, 2009). However, GHG emissions embodied in European imports have risen rapidly in the past 15 years (Peters and Hertwich, 2008; Wiedmann et al., 2010).

In terms of fresh water consumption, Europeans have higher Water Footprints per capita than the world average. Europe is one of the largest virtual water importers in the world (152 Gm^3 $year^{-1}$) with countries, especially in the south, highly dependent on foreign water resources for their consumption activities (up to 50–80% of the total Water Footprint value) (Chapagain and Hoekstra, 2004).

A shift to a more sustainable future thus requires a qualitative and quantitative understanding of the drivers in play (production and consumption), as well as a significant mobilization and behavioral change of actors and institutions from all sides of the public, private, and consumer spheres.

4.2. The EU Policy Context

In the last five years, the European Commission (EC) has launched several strategies to account for the main drivers of Europe's use of natural resources and related environmental impacts (e.g., the 'Sustainable Development Strategy' and the 'Thematic Strategy on the Sustainable Use of Natural Resources'). The issue of resource efficiency gained further policy support in the new 10-year economic strategy of the EU adopted by EU head of states in June 2010. This so-called "Europe 2020" strategy demands the transformation towards green, resource efficient growth and aims at implementing an EU "flagship initiative" on resource efficiency from 2011 onwards.

Despite widespread support in different EU policies for issues such as resource efficiency and environmental impacts, little concrete action has been taken. No quantitative targets have been formulated in any of the main EU policies, which rather remain on a general level of declarations of intent, without detailing concrete policy measures.

The OPEN:EU project originates from the willingness to answer the renewed EU Sustainable Development Strategy (SDS) call for the development of indicators able to capture the full complexity of Sustainable Development. To this end, the Footprint Family suite of indicators has been introduced and its potential policy usefulness explored in the section below.

4.3. Policy usefulness of the Footprint Family

In the attempt to identify indicators to best address the environmental issues European policy makers are facing, the Footprint Family has been tested against some of the main European (and international) policy objectives and outcomes summarized in Fig. 1. Each spider graph states the policies for which each indicator is fully (100), sufficiently (75), partially (50), marginally (25) or not relevant at all (0). These graphs show how relevant the single indicator and the Footprint Family are for informing these policies, i.e., the degree to which results provided by the indicator informs the policy. However, this does not imply that the policies could sufficiently be informed by these indicators or that the indicators could model the impacts of these policies. Only the most relevant policy and policy fields have been considered in this analysis; additional information can be found in Galli et al. (2011b) and Knoblauch and Neubauer (2010).

Concerning the EU Sustainable Development Strategy (SDS), the Footprint Family was found partly suitable to inform policy makers as each of the indicators in the suite provides information relevant for the strategy but, even combined, they do not cover all the policy fields listed in the strategy (Knoblauch and Neubauer, 2010). In particular, out of the seven key challenges of the SDS, only three (climate change and clean energy; sustainable production and consumption; conservation and management of natural resources) can be informed by the Footprint Family, while the other four (sustainable transport; public health; social inclusion, demography and migration; and global poverty and sustainable development challenges) are not covered.

Four main priority areas are included in the EU 6th Environmental Action Plan (6EAP): climate change; nature and biodiversity; environment, health and quality of life; natural resources and wastes. Of these, the Ecological Footprint is partly suitable to inform on 'nature and biodiversity' as well as 'natural resources and wastes', although only CO_2 emissions are tracked by this indicator and numerous other environmental impacts (e.g., toxic emissions, nuclear wastes production, etc.) are not considered. When used in combination with Human Development Index (Ewing et al., 2010), the Ecological Footprint can also partly inform on 'environment, health and quality of life'. Carbon Footprint is only partly suitable to inform about 'climate change' as it informs about GHG emissions but not about the potential alterations to climate. Given its capacity to track human use and pollution of freshwater resources, Water Footprint partly informs about 'natural resources and waste'.

Four of the seven Thematic Strategies (TS) within the 6EAP can be partly informed by the Footprint Family: Carbon Footprint partly informs the TS on air pollution (TS Air) and the TS on sustainable use of natural resources (TS Resources); Water Footprint partly informs the TS on the marine environment (TS Marine) and, for what concern water, the TS on sustainable use of natural resources (TS Resources); Ecological Footprint partly informs the TS on the prevention and recycling of waste (at least indirectly through addressing the overexploitation) (TS Waste) and the TS on sustainable use of natural resources (TS Resources). More precisely, the Ecological Footprint can sufficiently inform on the use of renewable resources but is not informative at all on the use of non-renewable resources (see Best et al., 2008 for further details on the role of the Ecological Footprint regarding TS Resources). The remaining three thematic strategies (urban environment, sustainable use of pesticides and soil protection) cannot be informed by the Footprint Family and its indicators.

The 2005 Lisbon Strategy primarily focused on social and economic aspects and thus none of the indicators is suitable to

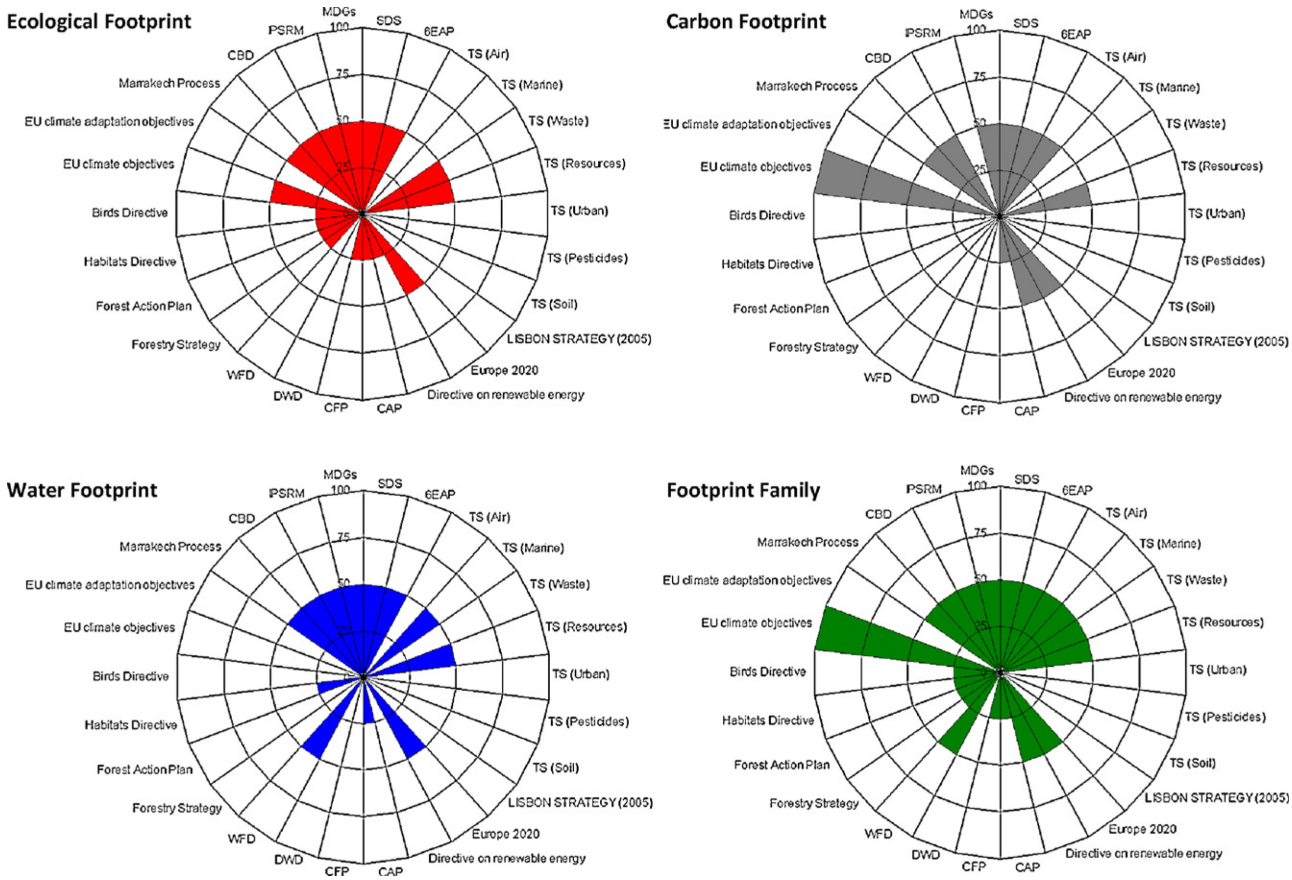

Fig. 1. Indicator-policy radar. The radar summarizes the range of applicability and the depth of the assessment for each of the Footprint indicators as well as the whole Footprint Family. For any given policy, the radar highlights whether the indicator is able to address policy *fully* (100), *sufficiently* (75), *partially* (50), *marginally* (25) or *not at all* (0). Acronyms for policies are as follows: SDS – EU Sustainable Development Strategy; 6EAP – EU Sixth Environmental Action Programme; TS – Thematic Strategies; CAP – Common Agricultural Policy; CFP – Common Fisheries Policy; DWD – Drinking Water Directive; WFD – Water Framework Directive; CBD – Convention on Biological Diversity; IPSRM – International Panel for Sustainable Resource Management; MDGs – UN Millennium Development Goals.

inform policy makers for this strategy. Conversely, the Europe 2020 Strategy includes environmental and climate targets and thus the Ecological, Water, and Carbon Footprint are partly suitable to inform on the headline target of the renewed strategy: Carbon Footprint informs on the headline target to reduce the GHG emissions; Ecological and Water Footprint inform on the flagship initiative on a "Resource Efficient Europe". However, most of the headline targets and flagship initiatives focus on issues such as employment rates, share of early school leavers, poverty, youth, internet, etc., that cannot be informed by the Footprint Family.

The Directive on renewable energy (Directive 2009/28/EC), the Forestry Strategy as well as the Forest Action Plan are all resource related policies and the Ecological Footprint was found to be marginally informative to address them (Knoblauch and Neubauer, 2010). However, the Ecological Footprint is unable to inform on non-renewable resources and, being an aggregated indicator, it is not suitable to inform policy makers on resource-specific policies (e.g., forests). The Directive on renewable energy is partially informed by the Carbon Footprint.

The various water use policies – especially those addressing water scarcity and resource productivity – can partially be informed by the Water Footprint (e.g., Water Framework Directive – WFD). For instance, Spain was the first country to include Water Footprint analysis into governmental policy making in the WFD context. However, due to data limitations and the consequent assumptions, it was found difficult to derive conclusions for practical policies from the Water Footprint values and therefore support in gathering better and nation specific data would be needed. Furthermore, the grey Water Footprint component could be used to inform on water pollution. However, the reliability and robustness of the grey component of the Water Footprint is heavily affected by the lack of proper data (Hoekstra et al., 2009). Finally, Water Footprint was found to be not informative regarding the Drinking Water Directive (DWD).

The Common Fisheries Policy (CFP) defines the type and amount of fish that each Member State is allowed to catch. Given the inclusion of fishing ground biocapacity and Footprint in its calculation, the Ecological Footprint could be potentially suitable to addresses the CFP. However, because of methodological and data issues, the current fishing grounds Ecological Footprint and biocapacity trends are not able to show fish stock depletion. As such additional research is mandatory (Ewing et al., 2010; Kitzes et al., 2009) to improve the fishing ground calculation before the Ecological Footprint can be used to inform the CFP. Preliminary attempts in this direction have been initiated in the United Arab Emirates via collaboration between Global Footprint Network and government bodies (Hartmann et al., 2010).

The climate related policies reported in Fig. 1 can be partly informed by the Carbon Footprint. It has been suggested that the most serious consequences of global warming might be avoided if global average temperatures rose by no more than 2 °C above pre-industrial levels (IPCC, 2007b). Recent research suggests that it would be necessary to achieve stabilization below 400 ppm of carbon dioxide in the atmosphere (ideally 350 ppm) to give a relatively high certainty of not exceeding 2 °C increase (Hansen et al., 2008; Rockström et al., 2009). As of 2010, carbon dioxide concentration in the Earth's atmosphere was approximately 390 ppm; this renders any additional emissions as 'unsustainable' and the Carbon Footprint informative to cover the issue. None of the indicators covers issues such as nuclear impacts, toxicity or radioactive emissions and wastes (see also section 4.4).

In monitoring world progresses towards the CBD 2010 biodiversity targets (Butchart et al., 2010), the Ecological Footprint has been used by the Biodiversity Indicator Partnership (BIP) as a measure of combined human pressure on ecosystems and biodiversity. Within the context of the CBD 2011–2020 Strategic Plan for biodiversity (CBD, 2010), the Ecological Footprint has been proposed as one of the indicator to be used in monitoring progresses towards the implementation of Target 4 of the plan "*By 2020, at the latest, Governments, business and stakeholders at all levels have taken steps to achieve or have implemented plans for sustainable production and consumption and have kept the impacts of use of natural resources well within safe ecological limits*". Carbon and Water Footprint can complement the Ecological Footprint by monitoring different aspects of the human pressure on ecosystems and biodiversity (GEO BON, 2011).

The Footprint Family is partly suited to inform policy makers on the UN Millennium Development Goals (MDGs), especially on Goal 7 (Ensure Environmental Sustainability) as it refers to resource use/deforestation, climate change and drinking water. The three indicators can also inform on issues such as inequality in resource accessibility and use. As such, the Footprint Family can be used to partially inform on Goal 8 (Develop a global partnership for development) or linked to policy debates in the development policy area (e.g., fair share, contraction and convergence, environmental justice). All other MDGs cannot be informed by the Footprint Family.

The International Panel for Sustainable Resource Management (IPSRM) observes, among others, exploitation of resources. The Ecological Footprint is fully suitable to inform on exploitation of renewable resources; the Water Footprint informs about the issues related to water use and productivity. However, Ecological and Water Footprint cannot inform on issues related to non-renewable resources (see Section 4.4). By contrast, the Carbon Footprint is not dealing with resource exploitation and is thus not informative for IPSRM.

The Marrakech Process deals with sustainable consumption and production issues. The Ecological, Water, and Carbon Footprint are also dealing with consumption and production issues and they can thus be used to inform the process. Moreover, with the development and implementation of a streamlined MRIO-Footprint model (Hawkins et al., forthcoming), the Footprint Family will better inform these processes via linking the information on consumption and production. Grouped within such model, the Footprint Family will trace Footprints along the full supply chain thus connecting consumption activities with various forms of pressure due to the production phase worldwide.

Since the adoption of the Health Check, new challenges have been highlighted for the future Common Agricultural Policy (CAP): climate change, better water management, the affects upon biodiversity, and the production of green energy. However, activities and measures resulting from these challenges and further debated within the ongoing CAP reform process can marginally be informed by the Footprint Family.

The Habitats Directive (Directive 92/43/EEC) and the Birds Directive (Directive 2009/147/EC) aim to protect habitats and species. These directives can be marginally – and only indirectly – informed by the Footprint Family via the Ecological and Water Footprint. Theoretically, these two indicators could be used to explore the aggregate pressure humans place on various ecosystems and habitats. However, the relationships between Footprint indicators and biodiversity have been explored only in a theoretical and qualitative way. Additional research is mandatory to determine whether such relationships can be established from a quantitative point of view and the outcomes strong enough to be significant to inform policies. The Carbon Footprint was found not informative for these directives.

4.4. Footprint Family: limitations and potential improvements

The Footprint Family concept developed by the OPEN:EU project represents a first attempt at creating a consumer-based suite of indicators enabling EU decision makers to monitor progresses towards a One Planet Economy: *an economy that respects all environmental limits and is socially and financially sustainable, enabling people and nature to thrive*. However, as it currently stands, the Footprint Family is unable to address social and financial aspects and somehow limited in its capacity to track environmental limits.

To address the first drawback, it has been suggested (OPEN:EU, 2010) to qualitatively link the Footprint Family with a wide range of socio-economic indicators addressing issues such as material well-being, income and consumption levels, income distribution, health conditions and health expectancy, access to education, personal activity (including work and unemployment), political voice and governance, social connections and relationships as well as physical and financial insecurity (Stiglitz et al., 2009). This would enable monitoring human-induced environmental pressures and understanding the potential implications for country's economies and citizen's well-being.

Regarding the second shortcoming, the Footprint Family is currently unable to address, among others, relevant environmental issues such as soil quality and land degradation due to intensive agricultural practices, ecosystems' eutrophication due to nitrogen deposition, release of toxic compounds, depletion of non-renewable resources and the many issues related to nuclear energy and nuclear waste. To better track the environmental impacts of production and consumption activities and assess trade-offs, the Footprint Family could thus benefit from the inclusion in the suite of additional footprint-type of indicators such as 'nuclear' (Stoeglehner et al., 2005; Wada, 2010) and 'nitrogen' (see http://www.n-print.org/) footprints. Unfortunately, the methodologies for these indicators are not yet as standardized and robust as in the case of Ecological, Carbon and Water Footprint, wherefore additional research is needed before potential inclusion in the Footprint Family. Building on material flow accounting (Giljum et al., 2011), some sort of 'material footprint' could also be developed and included in the suite to track production and consumption of non-renewable materials such as metal ores and other minerals. This would allow comparing the use of mineral resources with the Earth's regenerative capacity for them, thus enabling the Footprint Family to also track human pressure on the *lithosphere*.

Finally, overlaps have been identified within the Footprint Family, especially between Carbon and Ecological Footprint. Despite the methodological differences reported in Section 3.1, the carbon component of the Ecological Footprint (carbon uptake land) partly overlaps with the Carbon Footprint. To make the two indicators less correlated while maintaining the same range of application of the current Footprint Family, one could argue for the removal of the 'carbon uptake land' from the Ecological Footprint methodology. Conversely, to preserve the ability to assess trade-off within the single value provided by the Ecological Footprint, one could call for the strengthening of this indicator through the inclusion of the whole set of GHGs rather than just CO_2. A detailed description of pros and cons of including other GHGs in the Ecological Footprint methodology, as well as a review of methodological proposals for such inclusion can be found in Kitzes et al. (2009).

5. Conclusion

The Footprint Family concept introduced in this study is intended to assist policy makers as well as academics, CSOs, and other practitioners in understanding the diverse pressures human activities place on the planet. It represents a quantifiable and rational basis on which to begin discussions and develop answers on the limits to natural resource and freshwater consumption, greenhouse gas emissions, as well as on how to address the sustainability of natural capital use across the globe.

The need for developing such a suite of indicators originates from the understanding that, when used in isolation, each of the indicators considered in this paper is able to capture a limited range of the full complexity of sustainable development. As a result, there is a lack in the indicators realm of methods and tools with which to fully illustrate the links between economic growth and environmental degradation to policy makers, CSOs and the public.

The Footprint Family proposed here can thus be used to improve researchers' ability to track the current resource use and the impact this use generates, highlight the main drivers of resource use (therefore providing information on the areas where actions are needed), suggest solutions, and quantify the outcomes of specific policies undertaken to reduce the negative environmental impacts of natural resource use. However, relevant sustainability-related topics including human health and well-being cannot be tracked with the Footprint Family.

The three indicators selected are all characterized by the capacity to represent the environmental consequences of human activities, though they are built around different research questions and tell different stories. The Ecological, Carbon and Water Footprint have to be regarded as complementary in the sustainability debate and the Footprint Family as a tool able to track human pressures on various life-supporting compartments of the Earth (*biosphere*, *atmosphere*, and *hydrosphere*).

This does not mean that the Footprint Family is a fully inclusive and comprehensive basket of indicators nor that it should be considered as the sole tool decision makers should rely on. However, if Europe, or any other region, is to truly address sustainable development then decision makers need multiple tools and sets of indicators, one of which could be the Footprint Family. In reducing resource consumption while improving economic well-being, all biosphere's compartments need to be taken into account and trade-offs understood to avoid additional cost, or worse, inadvertently undoing progress in one sector by not accounting for direct and indirect implications of actions in other sectors.

Of the three indicators, the Ecological Footprint was found to have the widest spectrum of applicability, though only the Thematic Strategy on the sustainable use of natural resources and the International Panel for Sustainable Resource Management were found to be sufficiently and directly addressed by this indicator. Conversely, the Carbon Footprint was found directly able to address the EU Climate Objectives, though its range of applicability was found to be very narrow. The Water Footprint was found to have a restricted range of applicability and to be sufficiently informative for the EU water policies only. Although not yet comprehensive and unable to track some relevant environmental, economic and social issues, the Footprint Family was found to cover a wide-enough spectrum of policies and, particularly for what concern sustainable production and consumption issues, it is believed to be informative for policy and decision makers to a satisfactory extent.

Acknowledgments

We would like to thank Gemma Cranston (Global Footprint Network), Katy Roelich (Stockholm Environment Institute), Alexander Neubauer (Ecologic Institute) and Troy Hawkins (Norwegian Institute of Science and Technology) for their comments and feedback. Thanks are also due to Valentina Niccolucci and Nicoletta Patrizi (University of Siena), Justin Kitzes (University of Berkeley) and Paul Wermer (Paul Wermer Sustainability Consulting) for their initial feedback and comments on the Footprint Family concept. We would like to also thank the two anonymous reviewers of this paper for their positive and constructive comments. Finally, we would like to acknowledge the role of the EC Commission in funding the One Planet Economy Network Europe project as part of its Seventh Framework Programme (FP7), as well as that of the WWF UK team in managing the OPEN:EU project. At the time of writing the manuscript Thomas Wiedmann was employed at the Stockholm Environment Institute, University of York, York, UK and Brad Ewing was employed at Global Footprint Network, CA, USA.

References

Alcamo, J., Henrichs, T., Rösch, T., 2000. World Water in 2025–Global Modeling and Scenario Analysis for the World Commission on Water for the 21st Century. Report A0002, Center for Environmental Systems Research, University of Kassel, Kurt Wolters Strasse 3, 34109 Kassel, Germany.

Allan, J.A., 1998. Virtual water: a strategic resource, global solutions to regional deficits. Groundwater 36 (4), 545–546.

Bastianoni, S., Pulselli, F.M., Tiezzi, E., 2004. The problem of assigning responsibility for greenhouse gas emissions. Ecological Economics 49, 253–257.

Bastianoni, S., Niccolucci, V., Pulselli, R.M., Marchettini, N., this issue. Indicator and Indicandum: "sustainable way" vs. "prevailing conditions" in Ecological Footprint definition.

Behrens, A., Giljum, S., Kovanda, J., Niza, S., 2007. The material basis of the global economy. World-wide patterns in natural resource extraction and their implications for sustainable resource use policies. Ecological Economics 64, 444–453.

Best, A., Giljum, S., Simmons, C., Blobel, D., Lewis, K., Hammer, M., Cavalieri, S., Lutter, S., Maguire, C., 2008. Potential of the Ecological Footprint for monitoring environmental impacts from natural resource use: analysis of the potential of the Ecological Footprint and related assessment tools for use in the EU's Thematic Strategy on the Sustainable Use of Natural Resources. Report to the European Commission, DG Environment.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Hernández Morcillo, M., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.-C., Watson, R., 2010. Global biodiversity: indicators of recent declines. Science 328, 1164–1168, doi:10.1126/science.1187512.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water Footprints of nations. Value of Water Research Report Series No. 16, UNESCO-IHE, Delft, The Netherlands. http://www.waterfootprint.org/Reports/Report16Vol1.pdf (accessed 10.10.10).

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

Dittrich, M., 2009. The physical dimension of international trade, 1962–2005. In: Bleischwitz, R., Welfens, P.J.J., Zhang, Z.X. (Eds.), Sustainable Growth and Resource Productivity. Economic and Global Policy Issues. Greenleaf Publishing, Sheffield, UK.

EEA (European Environmental Agency), 2009. Greenhouse gas emission trends and projections in Europe 2009. Tracking progress towards Kyoto targets. European Environment Agency, Copenhagen.

Erb, K.H., Krausmann, F., Lucht, W., Haberl, H., 2009. Embodied HANPP: mapping the spatial disconnect between global biomass production and consumption. Ecological Economics 69, 328–334.

Ewing B., Moore, D., Goldfinger, S., Oursler, A., Reed, A., Wackernagel, M., 2010. Ecological Footprint Atlas 2010. Global Footprint Network, Oakland. http://www.footprintnetwork.org/images/uploads/Ecological%20Footprint%20Atlas%202010.pdf (accessed 12.10.10).

Falkenmark, M., 1989. The massive water scarcity now threatening Africa: Why isn't it being addressed? Ambio 18 (2), 112–118.

Fischer-Kowalski, M., Haberl, H., 2007. Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar, Cheltenham, UK.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Stuart Chapin, F., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Colin Prentice, I., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Galli, A., Kitzes, J., Niccolucci, V., Wackernagel, M., Wada, Y., Marchettini, N., 2011a. Assessing the global environmental consequences of economic growth through the ecological footprint: a focus on China and India. Ecological Indicators, doi:10.1016/j.ecolind.2011.04.022.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2011b. Integrating Ecological, Carbon and Water Footprint: Defining the "Footprint Family" and its Application in Tracking Human Pressure on the Planet. OPEN:EU project deliverable http://www.oneplaneteconomynetwork.org/resources/programme-documents/WP8_Integrating_Ecological_Carbon_Water_Footprint.pdf.

Galli, A., Kitzes, J., Wermer, P., Wackernagel, M., Niccolucci, V., Tiezzi, E., 2007. An exploration of the mathematics behind the ecological footprint. International Journal of Ecodynamics 2 (4), 250–257.

GEO BON (Group on Earth Observations – Biodiversity Observation Network), 2011. Adequacy of Existing Biodiversity Observation Systems to support the CBD 2020 Targets. Report in preparation for the Ad-Hoc Technical Expert Group on Indicators (AHTEG).

Giljum, S., Hinterberger, F., Bruckner, M., Burger, E., Frühmann, J., Lutter, S., Pirgmaier, E., Polzin, C., Waxwender, H., Kernegger, L., Warhurst, M., 2009a. Overconsumption? Our use of the world's natural resources. SERI, GLOBAL 2000, Friends of the Earth Europe.

Giljum, S., Hinterberger, F., Lutter, S., Polzin, C., 2009b. How to Measure Europe's Resource Use. An Analysis for Friends of the Earth Europe. Sustainable Europe Research Institute, Vienna.

Giljum, S., Burger, E., Hinterberger, F., Lutter, S., Bruckner, M., 2011. A comprehensive set of resource use indicators from the micro to the macro level. Resources, Conservation and Recycling 55, 300–308.

Global Footprint Network (GFN), 2010. Harmonizing the National Footprint Accounts with the System of Integrated Environmental and Economic Accounting. Paper number UNCEEA/5/11 prepared for discussion at the 5th Meeting of the UN Committee of Experts on Environmental-Economic Accounting, 23–25 June 2010, New York. http://unstats.un.org/unsd/envaccounting/ceea/meetings/UNCEEA-5-11.pdf (accessed 10.10.10).

Goudie, A., 1981. The Human Impact on the Natural Environment: Past, Present and Future. Blackwell Publishing, USA.

Haberl, H., 2006. The global socioeconomic energetic metabolism as a sustainability problem. Energy 31, 87–99.

Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Science 104, 12942–12947.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319 (5865), 948, doi:10.1126/science.1149345.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., Zachos, J.C., 2008. Target atmospheric CO_2: where should humanity aim? Open Atmospheric Science Journal 2, 217–231, doi:10.2174/1874282300802010217.

Hartmann, S., Reed, A., Galli A., 2010. Reflections on the fishing ground Footprint Methodology: the UAE as a case study. In: Bastianoni, S. (Ed.) Footprint Forum 2010: The State of the Art in Ecological Footprint Theory and Applications, pp. 53–54. http://www.footprintnetwork.org/images/uploads/Academic_Conference_Book_of_Abastracts.pdf (accessed 10.10.10).

Hawkins, T.R., Wiedmann, T.O., Ewing, B.R., Galli, A., Ercin, E.A., Weinzettel, J., Steen-Olsen, K., forthcoming. Integrating Ecological and Water Footprint Accounting in a Multi-Regional Input–Output Framework.

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environmental Science and Technology 43, 6414–6420.

Hoekstra, A.Y. (Ed.), 2003. Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Delft, The Netherlands, 12–13 December 2002, Value of Water Research Report Series No. 12, UNESCO-IHE, Delft, The Netherlands. www.waterfootprint.org/Reports/Report12.pdf (accessed 10.10.10).

Hoekstra, A.Y., Chapagain, A.K., 2007. Water Footprints of nations: water use by people as a function of their consumption pattern. Water Resources Management 21 (1), 35–48.

Hoekstra, A.Y., Chapagain, A.K., 2008. Globalization of Water: Sharing the Planet's Freshwater Resources. Blackwell Publishing, Oxford, UK.

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. Delft, The Netherlands.

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., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2009. Water Footprint Manual: State of the Art 2009. Water Footprint Network, Enschede, The Netherlands.

IPCC, 2007a. Climate change 2007: the physical science basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007b. Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Kitzes, J., Wackernagel, M., Loh, J., Peller, A., Goldfinger, S., Cheng, D., Tea, K., 2008a. Shrink and share: humanity's present and future ecological footprint. Philosophical Transactions of the Royal Society B 363, 467–475.

Kitzes, J., Galli, A., Rizk, S., Reed, A., Wackernagel, M., 2008b. Guidebook to the National Footprint Accounts: 2008 Edition. Global Footprint Network, Oakland.

Kitzes, J., Galli, A., Bagliani, M., Barrett, J., Dige, G., Ede, S., Erb, K.-H., Giljum, S., Haberl, H., Hails, C., Jungwirth, S., Lenzen, M., Lewis, K., Loh, J., Marchettini, N., Messinger, H., Milne, K., Moles, R., Monfreda, C., Moran, D., Nakano, K., Pyhälä, A., Rees, W., Simmons, C., Wackernagel, M., Wada, Y., Walsh, C., Wiedmann, T., 2009. A research agenda for improving national Ecological Footprint accounts. Ecological Economics 68 (7), 1991–2007.

Knoblauch, D., Neubauer, A., 2010. Pre-modelling analysis of the Footprint family of indicators in EU and international policy contexts. OPEN:EU project deliverable http://www.oneplaneteconomynetwork.org/index.html (accessed 10.10.10).

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.H., Haberl, H., Fischer-Kowalski, M., 2009. Growth in global materials use GDP and population during the 20th century. Ecological Economics 68 (10), 2696–2705.

Lenzen, M., Lundie, S., Bransgrove, G., Charet, L., Sack, F., 2003. Assessing the ecological footprint of a large metropolitan water supplier: lessons for water management and planning towards sustainability. Journal of Environmental Planning and Management 46, 113–141.

Lenzen, M., Murray, J., Sack, F., Wiedmann, T., 2007. Shared producer and consumer responsibility—theory and practice. Ecological Economics 61 (1), 27–42.

Lutz, C., Giljum, S., 2009. Global resource use in a business-as-usual world until 2030. Updated results from the GINFORS model. In: Bleischwitz, R., Welfens, P.J.J., Zhang, Z.X. (Eds.), Sustainable Growth and Resource Productivity. Economic and Global Policy Issues. Greenleaf Publishing.

Mekonnen, M.M., Hoekstra, A.Y., 2010. A global assessment of the green, blue and grey water footprint of crops and crop products. In Value of Water Research Report Series. UNESCO-IHE, Delft, The Netherlands.

Monfreda, C., Wackernagel, M., Deumling, D., 2004. Establishing national natural capital accounts based on detailed ecological footprint and biological capacity assessments. Land Use Policy 21, 231–246.

Moore, D., Galli, A., Cranston, G.R., Reed, A. Projecting future human demand on the Earth's regenerative capacity, this issue.

Nelson, G.C., Bennett, E., Berhe, A.A., Cassman, K., DeFries, R., Dietz, T., Dobermann, A., Dobson, A., Janetos, A., Levy, M., Marco, D., Nakicenovic, N., O'Neill, B., Norgaard, R., Petschel-Held, G., Ojima, D., Pingali, P., Watson, R., Zurek, M., 2006. Anthropogenic drivers of ecosystem change: an overview. Ecology and Society 11 (2), 29, http://www.ecologyandsociety.org/vol11/iss2/art29/ (accessed 10.10.10).

Niccolucci, V., Rugani, B., Botto, S., Gaggi, C., 2010. An integrated footprint based approach for environmental labelling of products: the case of drinking bottled water. International Journal of Design and Nature and Ecodynamics 5 (1), 68–75.

Niccolucci, V., Tiezzi, E., Pulselli, F.M., Capineri, C., this issue. Ecological Footprint vs. Biocapacity of world regions: a geopolitical interpretation.

OPEN:EU (One Planet Economy Network: Europe project), 2010. OPEN:EU Scenario Scoping Report. OPEN:EU project deliverable http://www.oneplaneteconomynetwork.org/resources/programme-documents/Scenario_Scoping_Report.pdf.

Patrizi, N., 2009. Approcci termodinamici per la valutazione della sostenibilità delle risorse idriche. PhD Thesis at the University of Siena–Department of Chemistry. Unpublished document (in Italian).

Peters, G.P., 2008. From production-based to consumption-based national emission inventories. Ecological Economics 65 (1), 13–23.

Peters, G.P., Hertwich, E., 2008. CO_2 embodied in international trade with implications for global climate policy. Environmental Science and Technology 42 (5), 1401–1407.

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. Global Biogeochemical Cycles 13 (4), 997–1027.

Ramankutty, N., Foley, J.A., Olejniczak, N.J., 2002. People on the land: changes in global population and croplands during the 20th century. Ambio 31 (3), 251–257.

Robinson, J., Bradley, M., Busby, P., Connor, D., Murray, A., Sampson, B., Soper, W., 2006. Climate change and sustainable development: realizing the opportunity. Ambio 35 (1), 2–8.

Rockström, R., Steffen, W., Noone, K., Persson, A., Chapin, 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., 2009. A safe operating space for humanity. Nature 461, 472–475.

Rosegrant, M.W., Cai, X., Cline, S.A., 2002. World Water and Food to 2025: Dealing with Scarcity. IFPRI, Washington, DC, USA.

Senbel, M., McDaniels, T., Dowlatabadi, H., 2003. The Ecological Footprint: a non-monetary metric of human consumption applied to North America. Global Environmental Change 13, 83–100.

Stiglitz, J.E., Sen, A., Fitoussi, J.P., 2009. Report by the Commission on the Measurement of Economic Performance and Social Progress.

Stoeglehner, G., Levy, J.K., Neugebauer, G.C., 2005. Improving the ecological footprint of nuclear energy: a risk-based lifecycle assessment approach for critical infrastructure systems. International Journal of Critical Infrastructures 1 (4), 394–403.

Sutton, P.C., Anderson, S.J., Tuttle, B.T., Morse, L. The Real Wealth of Nations: Mapping and monetizing the human Ecological Footprint, this issue.

Turner, G.H., 2008. A comparison of the limits to growth with 30 years of reality. Global Environmental Change 18, 397–411.

UNDP (United Nations Development Programme), 2006. Human Development Report 2006. Palgrave Macmillan, New York, USA. hdr.undp.org/hdr2006/ (accessed 10.10.10).

UNEP (United Nations Environment Programme), 2007. GEO_4 Global Environment Outlook: Environment for Development. Progress Press Ltd., Malta.

van den Bergh, J.C.J.M., Verbruggen, H., 1999. Spatial sustainability, trade and indicators: an evaluation of the "Ecological Footprint". Ecological Economics 29, 61–72.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.

Wackernagel, M., Onisto, L., Bello, P., Linares, A.C., Falfán, L., García, J.M., Suárez, G.A.I., Suárez, G.M.G., 1999a. National natural capital accounting with the ecological footprint concept. Ecological Economics 29 (3), 375–390.

Wackernagel, M., Lewan, L., Hansson, C.B., 1999b. Evaluating the use of natural capital with the ecological footprint. Ambio 28, 604–612.

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002. Tracking the ecological overshoot of the human economy. Proceedings of the National Academy of Science 99, 9266–9271.

Wada, Y., 2010. Responsibility allocation over time within Ecological Footprint Analysis: A case study of nuclear power generation. In: Bastianoni, S. (Ed.), Footprint Forum 2010: The State of the Art in Ecological Footprint Theory and Applications, pp. 159–160 http://www.footprintnetwork.org/images/uploads/Academic_Conference_Book_of_Abastracts.pdf (accessed 10.10.10).

Weinzettel, J., Steen-Olsen, K., Galli, A., Cranston, G., Ercin, E., Hawkins, T., Wiedmann, T., Hertwich, E., 2011. Footprint Family Technical Report: Integration into MRIO model. OPEN:EU project deliverable http://www.oneplaneteconomynetwork.org/resources/programme-documents/OPEN_EU_WP2_EC_Deliverable_Technical_Document.pdf.

Weisz, H., Lucht, W., 2009. Climate Change and Sustainable Use of Resources. Oral Presentations at the World Resources Forum 2009, Davos, Switzerland.

Weisz, H., Krausmann, F., Amann, C., Eisenmenger, N., Erb, K.H., Hubacek, K., Fischer-Kowalski, M., 2006. The physical economy of the European Union: cross-country comparison and determinants of material consumption. Ecological Economics 58 (4), 676–698.

Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecological Economics 69, 211–222.

Wiedmann, T., Barrett, J., 2010. A review of the ecological footprint indicator—perceptions and methods. Sustainability 2 (6), 1645–1693.

Wiedmann, T., Minx, J., 2008. A definition of 'Carbon Footprint'. In: Ecological Economics Research Trends. Nova Science Publishers, Hauppauge, NY, USA (chapter 1, pp. 1–11).

Wiedmann, T., Wood, R., Minx, J., Lenzen, M., Guan, D., Harris, R., 2010. A carbon footprint time series of the UK—results from a multi-region input–output model. Economic Systems Research 22 (1), 19–42.

WWF (WWF International), Global Footprint Network, ZSL (Zoological Society of London), 2010. Living Planet Report 2010. WWF, Gland, Switzerland. ISBN 978-2-940443-08-6. http://assets.panda.org/downloads/lpr2010.pdf (accessed 13.10.10).