Journal of Cleaner Production xxx (2015) 1–9

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Investigating the inventory and characterization aspects of footprinting methods: lessons for the classification and integration of footprints

Kai Fang [a, b, *], Reinout Heijungs [a, c]

[a] Institute of Environmental Sciences (CML), Leiden University, PO Box 9518, 2300 RA Leiden, The Netherlands
[b] School of Public Affairs, Zhejiang University, Yuhangtang Road 688, 310058 Hangzhou, China
[c] Department of Econometrics and Operations Research, VU University Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form
22 May 2015
Accepted 18 June 2015
Available online xxx

Keywords:
Footprints
Inventory analysis
Characterization
Weighting
Life cycle impact assessment

ABSTRACT

Inventory and characterization schemes play different roles in shaping a variety of footprint indicators. This paper performs a systematic and critical investigation of the hidden inventory aspect and characterization aspect of selected footprints with implications for classification and integration of those footprints. It shows that all of the carbon, water, land and material footprints have two fundamentally distinct versions, addressing the environmental exchange of substances in terms of emissions and/or extractions either at the inventory level or at the impact assessment level. We therefore differentiate two broad categories of footprints, namely the inventory-oriented footprints and the impact-oriented footprints. The former allow for a physical interpretation of human pressure by inventorying emissions and extractions and aggregating them with value-based weighting factors, whereas the latter assess and aggregate the inventory results according to their potential contributions to a specific environmental impact using science-based characterization factors, with the recognition that these contributing substances are too different to be compared by mass, volume or area. While both categories have individual strengths and weaknesses, the impact-oriented footprints have a better performance than the inventory-oriented footprints on the integration of footprints into a single-score metric in support of policy making. Resembling the general procedure for life cycle impact assessment, we formulate a three-step framework for characterization, normalization and weighting of a set of impact-oriented footprints to yield a composite footprint index, which would allow policy makers to better assess the overall environmental impacts of entities at multiple scales ranging from single products, organizations, nations, even to the whole economy. The main value added of this paper is the establishment of a unified framework for structuring, categorizing and integrating different footprints. It may serve as a starting point for clearing the footprint jungle and for facilitating the ongoing discourse on a truly integrated footprint family.

1. Introduction

Over the past years, a rapid expansion of footprint-style indicators has been introduced by companies, governmental bodies and non-governmental organizations, particularly in the field of environmental and sustainability sciences, with the goal of providing a series of pictures of what types of burden are imposed on the planet's environment, and to what extent. Nowadays footprints have reached worldwide popularity, and the environmental issues they are addressing become increasingly diverse, such as climate change (carbon footprint), freshwater use (water footprint), land use (land footprint), material use (material footprint), and so on.

Despite the prevalence of footprint indicators, most studies are narrowed down to one or a few footprints; this, however, brings the risk of problem shifting, as decline in one footprint is often accompanied by undesirable increase in others. For instance, although climate change in many cases dominates the total environmental footprints of a product (Finkbeiner et al., 2014; Page et al., 2012), reducing the carbon footprint is found to lead to a remarkable increase in other footprints (Laurent et al., 2012).

* Corresponding author. Institute of Environmental Sciences (CML), Leiden University, PO Box 9518, 2300 RA Leiden, The Netherlands. Tel.: +31 71 5271486.
E-mail addresses: fang@cml.leidenuniv.nl (K. Fang), heijungs@cml.leidenuniv.nl (R. Heijungs).

http://dx.doi.org/10.1016/j.jclepro.2015.06.086
0959-6526/

Similarly, De Meester et al. (2011) report that 27% of a bioproduct's carbon footprint is cut at the expense of 93% extra land, water and material footprints.

Since environmental issues are getting more and more complex arising from an ever-expanding number of stressors and their interactions (Chapman and Maher, 2014), a shift of focus from issues in isolation to simultaneous assessment in an overall view is needed. Consequently, the concept of "footprint family" was born, with the aim of informing policy makers about the overall environmental burden under a single framework without losing the complexity of the big picture (Galli et al., 2012). It was originated from the combination of the classical carbon, water and land footprints, but gradually extended to accommodate more emerging footprints (Fang et al., 2014; Ridoutt and Pfister, 2013a).

The footprint family concept implies the importance of finding ways to trade-off between different footprints and to minimize the total footprints from a system perspective, rather than emphasizing "net zero" solutions to individual footprints. This gives rise to concern for weighting, as trade-offs among footprints normally cannot be undertaken without any form of weighting (Finnveden et al., 2009; Ridoutt and Pfister, 2013a). The weighting sets have always been a highly controversial subject throughout integrated environmental assessment (Ahlroth et al., 2011). The difficulty of taking such a practice lies in the choice of weighting methods and in the way to deal with uncertainty (Finnveden et al., 2009). This is why weighting practices are basically lacking in present footprint family studies.

Nevertheless, when looking back at how different footprints are structured, we notice that some employ an inventory analysis merely, whereas some others perform an inventory analysis but also an impact assessment characterization. In many cases, unfortunately, the underlying structure has been executed implicitly and remains unexamined by footprint users. It is our conviction that lessons which can be learned from the hidden elements in single footprints will enormously facilitate the ongoing scientific discussions on footprint indicators, including the classification (Čuček et al., 2012), the complementary use and combination in a footprint family (Fang et al., 2014; Galli et al., 2012), and even a single weighted footprint metric (Ridoutt and Pfister, 2013a). This study may also be well connected to the policy domain, with potential to inform and support the development of existing environmental policy frameworks and projects, such as Product Environmental Footprint (EC, 2015), Environmental Footprint Analysis (EPA, 2014), PAS 2050 (BSI, 2011), and the related ISO standards (e.g., ISO, 2006).

This paper aims to propose a general conceptual and mathematical structure that underlies most, if not all, footprints that are en vogue at present, to achieve a harmonization of structure, terminology and notation, to distinguish the inventory aspect and the characterization aspect of different footprints, and to provide clarity on some theoretical issues underlying footprint methods. To that end, the remainder of this paper is structured as follows: Section 2 critically examines the inventory analysis and impact assessment characterization in each of the selected footprints; Section 3 offers insights on the implications of our findings for the classification and integration of footprints; discussion and conclusions are presented in Sections 4 and 5, respectively.

2. Investigation of the inventory and characterization aspects of selected footprints

2.1. Overall terminology and structure of the analysis

In theory, inventory analysis and impact assessment characterization are two successive steps for quantitatively modeling the consequences of man's exploitation of the nature. The fundamentals of the two elements are briefly stated as follows (Finkbeiner et al., 2014; Finnveden et al., 2009; Hauschild et al., 2013; Heijungs and Suh, 2002; Hellweg and Milà i Canals, 2014; Udo de Haes and Heijungs, 2009):

- **Inventory analysis**: a step aimed at tabulating and compiling the exchange of substances (i.e., emission of wastes to and extraction of resources from the environment) within the boundary of an investigated system (e.g., product, organization, nation). In the framework of life cycle assessment (LCA), this corresponds to life cycle inventory (LCI), a compilation of the inputs (resources) and the outputs (emissions) within the system boundaries of the study across its life cycle. The input and output substances are called elementary flows according to the ISO (2006). In the framework of substance flow analysis (SFA), it corresponds to the system definition and quantification (Van der Voet et al., 1995). In some analytical tools, this activity has no specific name, but it is recognizable as such; see, for instance, Eurostat (2014) for economy-wide material flow accounts (EW-MFA) and Miller and Blair (2009) for input–output analysis (IOA).
- **Impact assessment characterization**: a subsequent step aimed at assessing the inventory results according to their relative contributions to a specific environmental impact or a set of environmental impacts. In LCA, the contributing elementary flows are quantified using characterization factors and translated to common impact units to make them comparable and ready for aggregation into impact indicators. This step is known as life cycle impact assessment (LCIA), where characterization factors are derived from science-based models reflecting the environmental mechanism underlying the impact category under assessment. In MFA—an analytical tool to quantify material flows in well-defined systems, such steps are part of the interpretation of results (Van der Voet et al., 1995). Again, in EW-MFA and IOA, this activity is often present, although without an explicit name. Characterization factors are part of the LCIA-specific jargon, but such factors are used by many other studies as well (e.g., Fuglestvedt et al., 2008; Skeie et al., 2009).

A general mathematical framework for the two steps is as follows. Let M_i be the quantified emission or extraction of substance i (e.g., kg, kg/yr, m^3/yr). Inventory analysis proceeds according to:

$$M_i = \sum_k M_{ik} \tag{1}$$

where subscript k denotes all activities that emit or extract substance i within the system boundaries. The resulting inventories of the investigated system can be characterized with substance-specific characterization factors for a chosen impact category (e.g., climate change, resource scarcity) at midpoint or endpoint level:

$$I_j = \sum_i M_i \times cf_{ij} \tag{2}$$

where I_j is the indicator result for impact j (e.g., kg-eq., kg-eq./yr); and cf_{ij} is the characterization factor for substance i in relation to impact j (e.g., kg-eq./kg, m^3-eq./kg).

Alternatively, the resulting inventories of an investigated system can be weighted with weighting factors at the option of the users, particularly in cases where well-grounded characterization factors are not sufficiently available. We consider this as part of the