Environmental footprints: assessing anthropogenic effects on the planet's environment

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Chapter 3

Investigating the inventory and characterization aspects of footprinting methods

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Abstract

Inventory and characterization schemes play different roles in shaping a variety of footprint indicators. This chapter performs a systematic and critical investigation into the hidden inventory aspect and characterization aspect of selected environmental 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 environmental footprints, namely, the inventory-oriented footprints (IVOFs) and the impact-oriented footprints (IPOFs). 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 IPOFs have a better performance than the IVOFs 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 IPOFs 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 chapter 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.

3.1. 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). 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, 2013b).

The footprint family concept implies the importance of finding ways to trade-off between different footprints and to minimize the total environmental 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, 2013b). 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 environmental footprints are structured, we notice that some employ an inventory analysis merely, whereas some others perform an inventory analysis but also an impact 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, 2013b). 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 (PEF) (EC, 2015), Environmental Footprint Analysis (EPA, 2014), PAS 2050 (BSI, 2011), and the related ISO standards (e.g., ISO, 2006).

This chapter aims to propose a general conceptual and mathematical structure that underlies most, if not all, environmental footprints that are en vogue at present, to achieve a harmonization of structure, terminology and notation, to distinguish the inventory aspect and characterization aspect of different footprints, and to provide clarity on some theoretical issues underlying footprint methods. To that end, the remainder of this chapter is structured as follows: Section 3.2 critically examines the inventory analysis and impact characterization in each of the selected footprints; Section 3.3 offers insights on the implications of our findings for the classification and integration of footprints; discussion and conclusions are presented in Sections 3.4 and 3.5, respectively.

3.2. Investigation into the inventory and characterization aspects of selected environmental footprints

3.2.1. Overall terminology and structure of the analysis

In theory, inventory analysis and impact 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 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:

$$M_i = \sum_k M_{ik} \tag{3.1}$$

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:

$$I_j = \sum_i M_i \times cf_{ij} \tag{3.2}$$

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 inventory analysis, since no impact assessment has been done in the weighting step:

$$I'_j = \sum_i M_i \times iwf_{ij} \tag{3.3}$$

where I'_j is the indicator result *j* (e.g., kg, m^3, ha); and iwf_{ij} is the inventory weighting factor for substance *i* in relation to impact *j* (mostly dimensionless).

Note that, in this chapter, "inventory data" refers to the inputs of the inventory calculations (e.g., unit process data), "inventory results" in contrast refers to the outputs of the inventory calculations (e.g., system-wide emissions and extractions), and the weighted inventory results is out of the scope of these terms. Furthermore, weighting substances within a footprint, namely, inventory aggregation, should be distinguished from weighting footprints, which will be discussed in the following sections. For convenience, we name the former as "(inventory) weighting" and the latter as "(footprint) weighting". By contrast, in the field of LCA, the term "weighting" is restricted to what here we call footprint weighting (ISO, 2006). Inventory weighting is not recognized in the LCA standards, but in other tools for environmental assessment it may occur from time to time (e.g., Hoekstra and Hung, 2002).

In keeping with the framework described above, criteria are developed for selection prior to the evaluation of footprint indicators: (1) documentation of competing versions; (2) transparency in each of the methodologies; and (3) applicability to classification. For these concerns, a systematic and critical investigation into the inventory analysis and/or impact characterization will be presented specifically for four footprints: the carbon footprint, the water footprint, the land footprint, and the material footprint. For each of them, we identify two basic versions. It is worth mentioning that contrary to common practices, the ecological footprint in this chapter is presented in a disaggregate form. It means that we choose to separately investigate its abiotic and biotic components, as will be illustrated below.

3.2.2. Carbon footprint

3.2.2.1. Climate-related carbon footprint (CF_{clim})

The widely used climate-related carbon footprint (CF_{clim}) compiles the inventory data of greenhouse gas (GHG) emissions (e.g., CO_2, CH_4, N_2O) throughout the investigated system boundaries, and characterizes and aggregates them into a mass equivalent metric (e.g., kg CO_2-eq.) on the basis of their respective global warming potentials (GWPs)—a global-specific characterization factor representing the integrated radiative forcing over a specified time horizon, with a reference to CO_2 (IPCC, 2014; Wiedmann and Minx, 2008). While being arbitrarily configured by default to report a time horizon of 100-yr in practice, the GWP is deemed one of the most established and consensus-based characterization factors in LCIA (Hauschild et al., 2013; Laurent et al., 2012), and is also used much outside LCA. International consensus has thus been reached on the characterization modeling used for the CF_{clim} (Hellweg and Milà i Canals, 2014; Ridoutt and Pfister, 2013b). For the inventory part, however, there is much less agreement. In LCA, for instance, the issue of allocation of multi-functional processes is a nagging topic, and there is also disagreement on the accounting of biogenic carbon. In IOA, an example of the controversy is the choice between commodity-by-commodity tables and industry-by-industry tables. Once such inventory choices have been made, the characterization aspect runs smoothly.

3.2.2.2. Classical carbon footprint (CF_{class})

Although the carbon footprint is generally referred to as the CF_{clim}, the classical version of the carbon footprint (CF_{class}) was introduced about two decades ago by Wackernagel and Rees (1996), who convert carbon emissions from fossil energy into the emissions of CO_2 and then into the area of forest required to achieve carbon neutrality. This is why people also call it "energy footprint" (Fang et al., 2014). The CF_{class} premises that all carbon emissions are ideally emitted in the form of CO_2. Carbon contents (CCs) and carbon sequestration rate (CSR) are employed as parameters to make the two phases of conversion come true. Since the CSR is practically assigned with a fixed value of 970 kg/(ha·yr) for all cases (Blomqvist et al., 2013), the aggregation of multiple carbonaceous substances can be seen as a rough inventory analysis, in which the ratio of energy-specific CCs to the CSR serves as weighting factors for different types of fossil energy. It is not surprising that the scientific reliability and accuracy of its estimate have been debated (Blomqvist et al., 2013; Kitzes et al., 2009), thus excluding the CF_{class} from mainstream acceptance.

3.2.3. Water footprint

3.2.3.1. Classical water footprint (WF_{class})

The classical water footprint (WF_{class}) has received great popularity in past years, and its applications have been extended to a wide range of fields, in particular to the arena of basin water resources management (Hoekstra et al., 2009; Hoekstra and Hung, 2002). It measures and sums up the volumetric consumption of green, blue and gray water within an investigated system at the inventory level. The former two water components refer to the cubic meters of freshwater evaporated from the soil and ground surface, respectively, and the latter is expressed as the cubic meters of freshwater needed to dilute pollution below an acceptable standard (Chapagain and Hoekstra, 2008). The WF_{class} in general can be interpreted as an inventory analysis with regard to H_2O. However, its gray component is, to some extent, committed to an impact assessment because of the large similarity between the dilution approach used and certain characterization approaches (Kounina et al., 2013). Finally, the green, blue and gray components are aggregated without a clear characterization principle, signaling an inventory weighting aspect (even though the weighting factors are 1, i.e., equal weighting).

3.2.3.2. Scarcity-related water footprint (WF_{scarc})

In contrast to carbon emissions, which mix globally, water is a highly heterogeneous resource with varying impacts from region to region, which means that the same volumetric water consumption in places could trigger different degrees of water scarcity (Berger and Finkbeiner, 2013). Consequently, it is probably desirable to take local water scarcity into account. The scarcity-related water footprint (WF_{scarc}) complies with the inventory analysis of consumptive water use, and brings the water inventories into an impact characterization model where blue and/or green water are characterized with location-specific withdrawal-to-availability (WTA) ratios or analogous indices (Lenzen et al., 2013; Ridoutt and Pfister, 2010). It proceeds with the recognition that scarcity is the key to understanding the environmental relevance of local water consumption (Ridoutt and Huang, 2012). The final result of the WF_{scarc} is expressed in a H_2O-equivalent volumetric unit (e.g., m^3 H_2O-eq.) (Zonderland-Thomassen et al., 2014).

3.2.4. Land footprint

3.2.4.1. Classical land footprint (LF_{class})

Within the footprint family, the first quantification exercise is the case of the classical land footprint (LF_{class}) (Wackernagel and Rees, 1996). It converts hundreds of primary and secondary bioproducts into the area of cropland, grassland, woodland and fishing ground expressed in world-average bioproductivity. This conversion essentially corresponds to an inventory analysis, irrespective of the approximation of such a process. Bioproductivity, defined as an estimate of the biological production of a specific land type that can renewably support for human consumption (Kitzes et al., 2009; Lenzen et al., 2007), should not be viewed as a characterization factor due to the ambiguity of the impact assessed and the lack of confirmed environmental mechanism. According to the latest National Footprint Accounts (NFA) for the LF_{class}, the inventory weighting of different land use types is fulfilled through equivalence factors (EQFs)—a type of expert knowledge-based weighting assuming that the most suitable land type will be planted to cropland, and that woodland, grassland and fishing ground would be the second, third, and last choice (Borucke et al., 2013).

3.2.4.2. Disturbance-related land footprint ($LF_{disturb}$)

Having realized that the intensity of human-induced changes to land use considerably varies independently of bioproductivity, Lenzen and Murray (2001) come up with a revised version of the land footprint describing the degree of land disturbance ($LF_{disturb}$). All land types are reclassified and expressed in disturbed hectares, by multiplying the land inventories resulting directly from land cover survey or remote sensing with relative land disturbance factors (LDFs) (Kitzes et al., 2009; Lenzen et al., 2007). Contrary to the practitioners' belief, we consider LDF to be a characterization factor more than a weighting factor because disturbance has been identified as one of land use impacts (Udo de Haes, 2006). One may argue that the characterization model implemented in the $LF_{disturb}$ has not been formally validated by the global community. This is true, but land use in LCA is confronted with the same challenge (Klinglmair et al., 2014). For instance, while the ReCiPe method (Goedkoop et al., 2009) is the best among the existing characterization models for recommendation, the databases are nevertheless far from satisfactory and thus leave much room for improvement (Hauschild et al., 2013).

3.2.5. Material footprint

3.2.5.1. Classical material footprint (MF_{class})

The classical material footprint (MF_{class}) is a measure of abiotic and biotic resource use by adding up the quantity of a wide range of raw material consumption (e.g., metals, minerals, fossil energy) (Schoer et al., 2012; Wiedmann et al., 2015). In analogy to the LF_{class}, the MF_{class} commits to not only an inventory calculation, but also an aggregation of the inventory results. By means of the MF_{class}, one can be easily aware of the total resource needs of an investigated system. Interestingly, there is a tradition of summing up a great variety of materials at the kilogram level, as exemplified by the program of "the weight of nations" (Matthews et al., 2000). It should be noted that inventorying in this way is subject to equal weighting, implying that all material categories are regarded as equally important. It is likely to come to the conclusion that the MF_{class} is well suited to facilitating the dematerialization of production and consumption processes, rather than to reducing associated environmental impacts, as the ranking order of materials based on their environmental impacts can significantly deviate from that based on mass (Van der Voet et al., 2004).

3.2.5.2. Scarcity-related material footprint (MF_{scarc})

One obvious impact arising from material extraction is resource scarcity. Although different material categories are quite distinct in nature, they simultaneously contribute to the depletion of natural capital. A scarcity-related material footprint (MF_{scarc}) has been proposed in this context (Fang and Heijungs, 2014a). Given that water and land—two special but elemental resource categories have already been addressed by the water and land footprint accounts, and that most biotic resources can be reproduced by a production process and that this would hardly contribute to scarcity (Guinée et al., 1993; Guinée and Heijungs, 1995), the MF_{scarc} presently restricts its inventory analysis and impact assessment to the abiotic aspect. The MF_{scarc} is distinguished from the MF_{class} in that it substitutes abiotic depletion potentials (ADPs) for equal weighting factors and in that the outcome is expressed in equivalent units, with antimony (Sb) as a reference substance (e.g., kg Sb-eq.). It allows to characterize abiotic resources with respect to relative scarcity and to translate the overall risk of abiotic depletion into an understandable measure of kilograms (Fang and Heijungs, 2014a).

3.3. Lessons from the investigation for the classification and integration of environmental footprints

3.3.1. General lessons

On the basis of the investigation carried out, Figure 3.1 compares some key issues concerning the inventory aspect (including inventory weighting) and the characterization aspect across the footprints aforementioned. Major findings from the investigation are drawn as follows:

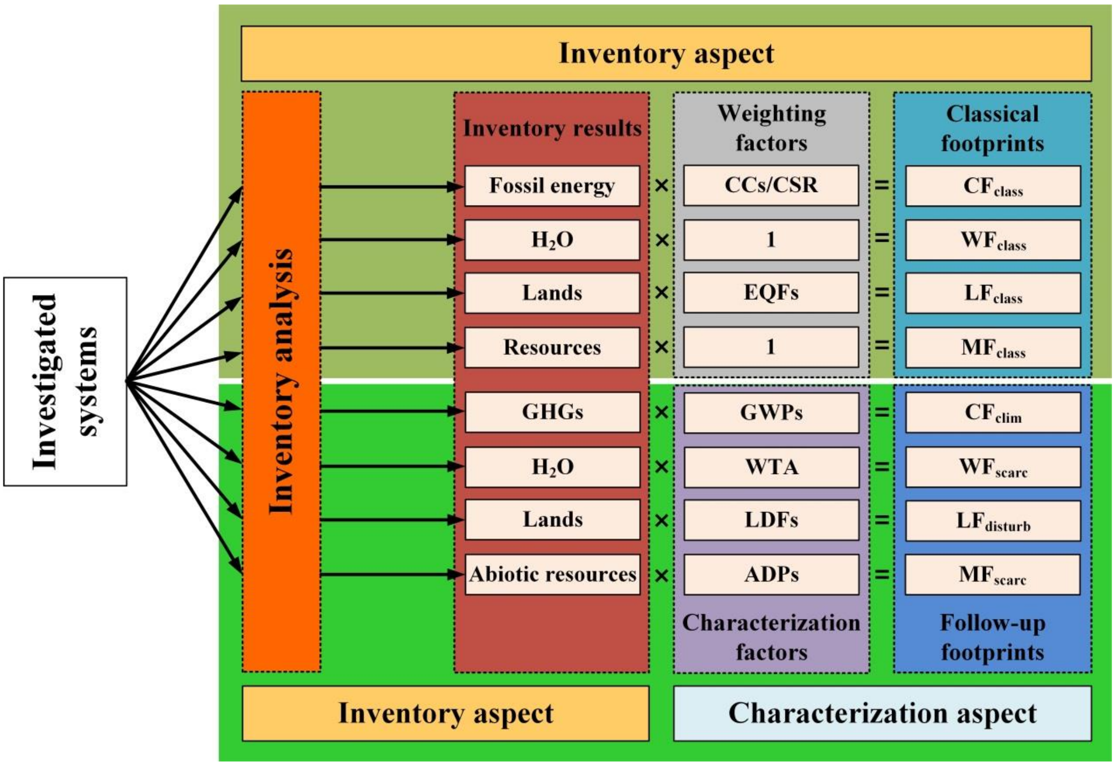

Figure 3.1. Schematic representation of the inventory and characterization aspects of selected footprints. While the inventory results are by and large aligned (some subtle points for CF_{class} and LF_{class} ignored here), two categories of footprints can be distinguished: those that weight inventory results, and those that characterize inventory results.

a) Each of the investigated footprints performs an inventory analysis, whereby data of wastes emitted to and/or resources extracted from the environment are tabulated and compiled specifically for defined system boundaries. The inventory can be LCA-based, and can be non-LCA-based as well. Alternatives to LCA include (parts of) IOA, MFA, NFA, and so on.

b) Some of the footprints further characterize the inventory results with characterization factors to yield single-score impact indicators expressed in equivalent units (e.g., kg CO_2-eq., m^3 H_2O-eq.), which is common to all contributing substances within each single impact category. This practice builds on the premise that environmental mechanism underlying the characterization modeling of the impact exists and can be modeled in a linear approximation as simple multiplication and addition.

c) In other cases, the inventory results are aggregated with weighting factors reflecting the relative importance based on expert-based judgments that contain social, political or ethical value choices in the study. It can be equal weighting in case that all factors are assigned with the same score, as is the case for the WF_{class} and for the MF_{class}. Unequal weighting is observed in the cases of the CF_{class} and LF_{class}. Whichever the weighting scheme, we consider this as part of inventory analysis, as no impact assessment has been done.

d) While the operational formulas are similar in style (both categories of footprints do a multiplication and addition), inventory weighting and impact characterization play different roles in bringing together various inventory results into a footprint. Weighting is value-based, typically using expert knowledge to express stated or revealed preferences and judgments. In contrast, characterization models are developed on the basis of recent scientific evidence, even though subjective choices cannot be completely avoided. The CF_{clim}, for instance, has substantially benefitted from the use of GWPs and had a much broader appeal than many other footprints, despite the arbitrary choice of time horizon.

e) Although the dichotomous framework for contrasting inventory weighting and impact characterization reveals valuable insights into the similarities and differences between these footprints, we admit that there is no sharp boundary between value-based weighting and science-based characterization. One example is the confusion surrounding the nature of the LDF used in the $LF_{disturb}$. This can be primarily attributed to the fact that a recognized consensus on land use characterization modeling is lacking (Hauschild et al., 2013). In view of the difficulties in assessing land use impacts, the $LF_{disturb}$ shows a relatively good performance on scientific robustness by tracing the causal linkages between biotic resource extraction, soil degradation, and biodiversity decline.

3.3.2. Lessons for the classification of footprints: a two-category framework

Simply put, environmental footprints are defined as indicators that measure anthropogenic pressure or associated impacts placed on the environment by human actions, irrespective of their precise units and dimensions. Rather than carrying on the never-ending debate over the definition of footprints, we propose shifting the focus to the classification of footprints which, in our view, is the key to making sense of the footprint concept. In accordance to the investigation conducted above, two broad categories of footprints are identified, namely, the IVOFs and IPOFs. This is a rough dichotomy with respect to the ways in which a growing number of footprints are shaped. In the following we elaborate on the two categories of footprints individually, together with a comparison of their inherent properties.

3.3.2.1. Inventory-oriented footprints (IVOFs)

The IVOFs are the footprints that compile and weight the inputs and outputs of environmental exchange (i.e., hazardous emissions and resource extractions) at the inventory level. It builds on the belief that physical units (e.g., ha, m^3, kg) provide an intuitive and intrinsic understanding of the anthropogenic pressure due to emissions and extractions, which is probably the original intent of what a footprint is supposed to convey to the public. This valuable information, however, is found to be lost when translating into an impact score through characterization modeling (Hoekstra et al., 2009). Apparently, all the four classical footprints, namely the CF_{class}, WF_{class}, LF_{class} and MF_{class}, fall under the scope of the IVOFs.

3.3.2.2. Impact-oriented footprints (IPOFs)

The IPOFs are those which not only comply with an inventory analysis but also characterize the inventory results through their respective contributions to a given impact category at the impact assessment level. The rationale behind the IPOFs is that contributing substances differ in their effects on the same impact category (sometimes by orders of magnitude), and therefore cannot be compared or aggregated without the use of characterization factors reflecting the up-to-date scientific knowledge about the effects of the impact category assessed on the environment and human health. We classify the CF_{clim}, WF_{scarc}, $LF_{disturb}$ and MF_{scarc} as members of the IPOFs. Nevertheless, one should be aware that while some IPOFs use physical-look-alikes units (e.g., the CF_{clim} uses kg CO_2-eq.), such units differ markedly from the real measurable footprints in the IVOF category.

3.3.2.3. Comparison of the two footprint categories

An overall comparison between the IVOFs and IPOFs in terms of some inherent properties is presented in Table 3.1. As shown, the two categories of footprints differ mostly in the ways they address the inventory results. The IVOFs apply value-based weighting to the aggregation of inventory results, whereas the IPOFs are more concerned with the consequences for environmental quality by processing the inventory results with science-based characterization factors.

To further delineate the difference of interpretation between the two footprint categories, we briefly present an illustrative comparison of the WF_{class} and WF_{scarc} for a product system. From an LCA perspective, the WF_{class} deals with the inventory aspect of water use over the product's life cycle, which could serve as a preparatory step to advanced impact assessment. In other words, a subsequent step is to assess the associated environmental impacts using one or more characterization models. Water scarcity that the WF_{scarc} describes is just one of the many environmental consequences resulting from consumptive and degradative water use. Other impacts at midpoint level may include eutrophication (Zonderland-Thomassen et al., 2014) and human toxicity (Boulay et al., 2011), for instance. This is in contrast to endpoint characterization where impacts refer to damage to several of the areas of protection, like human health (Ridoutt and Pfister, 2013a) and ecosystem quality (Hanafiah et al., 2011). All this goes beyond water quantity and thereby constitutes an expanding list of impact/damage-oriented water footprints.

Table 3.1. Comparison of the inventory-oriented and impact-oriented footprints.

Item	Inventory-oriented footprints (IVOFs)	Impact-oriented footprints (IPOFs)
Examples	CF_{class}, WF_{class}, LF_{class}, MF_{class}	CF_{clim}, WF_{scarc}, $LF_{disturb}$, MF_{scarc}
Factors for inventory aggregation	Weighting factors: reflecting the relative importance based on value-based judgments. Easily obtainable but subjective and not reflecting the latest scientific knowledge.	Characterization factors: representing the relative contributions of substances to a specific impact category. Primarily science-based although including some subjective choices.
Rationale	Inventory analysis of contributing substances enables a physical interpretation of human pressure and this may disappear if translating into an impact result through characterization modeling.	Different substances per physical unit vary so notably within any single impact category that they cannot be directly compared and aggregated at the inventory level.
Strengths	Compiling different emissions and extractions with understandable physical units and laying an inventory basis for communicational purposes.	Linking quantitative inventory results to a specific environmental impact and assessing the impact on a scientific characterization basis.
Weaknesses	Not revealing the environmental relevance of different emissions and extractions with respect to their relative contributions to environmental impacts.	Not revealing the physical meaning of emissions and extractions exerted by human activities.
Applicability	Typically oriented towards the macro-level of economy (global, nation-wide, etc.).	Typically oriented towards the micro- or meso-level of individual products or processes.
Policy relevance	Instrumental for policies aimed at measuring the pressure of resource use on the environment and at identifying the driving forces that are causing environmental problems.	Instrumental for policies aimed at assessing potential environmental impacts of emissions and extractions and at finding alternatives for the reduction of impacts.

3.3.3. Lessons for the integration of footprints: a three-step framework

The variation in potential environmental impacts associated with a single stressor (e.g., water use) brings our attention back to the weighting between footprints, referred to as footprint weighting in this chapter. Though the two categories of footprints discussed above both have pros and cons, we argue below that only the IPOFs have the capacity to be integrated into a single composite metric. After that we propose a three-step framework for the integration of IPOFs.

3.3.3.1. The rationale of choosing the IPOFs for integration

There are two main reasons for choosing the IPOFs rather than choosing the IVOFs when it comes to integrating different footprints into one single-score metric:

a) Each IPOF characterized with science-based characterization factor is pinpointing a well-defined impact category such as climate change and water scarcity. Collectively, they are particularly suited to forming an overall picture of the integrated environmental impacts of a product, organization, or nation, without obvious overlapping. This is different from the IVOFs, for which double counting may occur. The WF_{class}, for instance, juxtaposes water use, depletion, and pollution. The pollution part may easily overlap with a chemical or toxic footprint, and it appears difficult to attach a weight to such a heterogeneous footprint.

b) Footprint weighting in the integration of footprints is unavoidable, whereas inventory weighting in shaping a single footprint can be avoided by making use of characterization factors that bring together different inventory results into an IPOF footprint with the best available scientific knowledge on natural resources, human health and environmental impacts. Compared with the IVOFs, the IPOFs have a better performance in the sense that they are able to achieve this integration without performing a double weighting that would certainly compromise the validity of the final estimate.

To sum, double counting and double weighting can be avoided by using the IPOFs rather than using the IVOFs.

3.3.3.2. An initial framework for characterization, normalization and weighting of the IPOFs

Now it seems to be clear that the integration of environmental footprints only makes sense if all involved are members of the IPOF category, to which knowledge of LCIA would be of great benefit. In the LCA framework, LCIA takes place as a subsequent step to LCI, where a number of elementary flows are translated into single impact indicators and, if desired, then weighted and integrated into a comprehensive metric. Essentially, LCIA consists of three major steps: characterization, normalization, and weighting. While according to ISO (2006) the weighting is optional and not recommended for comparative assertions communicated to the public because of the subjectivity and uncertainty, weighting between impact categories greatly facilitates policy making (Hellweg and Milà i Canals, 2014). This is particularly true for analysis aimed at informing policy makers who are in favor of weighted indicators that make alternatives easily comparable (Ahlroth et al, 2011). Therefore, footprint weighting in our view can be considered as part of the established practice although it should be interpreted with caution (Fang et al., 2015). This is moreover a logical extension to the idea of the footprint family that is mainly limited to a conceptual discussion.

To cite an example, we assume that, along the life cycle of a product system, all of the required data are available. In that case, many conceivable IPOFs can be imitated by multiplying the inventory results with corresponding characterization factors such as ozone depletion potential (ODP), terrestrial acidification potential (TAP), and aquatic ecotoxicity potential (AEP). Returning to the mathematical formulation in Section 3.2.1, we calculate a set of *IPOFj* through:

$$IPOF_j = \sum_i M_i \times cf_{ij} \tag{3.4}$$

The outcome is impact indicators expressed in equivalent units (e.g., kg CFC-11-eq., kg SO_2-eq., kg 1,4-DCB-eq.), which are common to all contributing substances within the impact category, but not across impact categories due to incomparable units. This is why normalization is needed after characterization. The calculation principle of normalization is transparent (Heijungs et al., 2007): each normalized footprint $nIPOF_j$ is equal to the ratio of the product footprint to the reference system's footprint for that category $IPOF_{ref,j}$:

$$nIPOF_j = \frac{IPOF_j}{IPOF_{ref,j}} \tag{3.5}$$

The globe is in many cases the most suitable reference system, because a single product may also have a global coverage of waste emission and resource extraction in today's globalized economy (Guinée et al., 2002). However, for some regional-specific impacts, the reference system can specify by a continent scale like Europe or North America (Hauschild et al., 2013; Laurent et al., 2012). The footprints for the reference are usually calculated through inventorying the emissions and extractions of the reference system and subjecting it to the same footprint calculations:

$$IPOF_{ref,j} = \sum_i M_{ref,i} \times cf_{ij} \tag{3.6}$$

By translating abstract impact results into relative contributions of the product to a reference situation, the normalized footprint results (e.g., yr) allow for a direct comparison between impact categories at a broader context. Nevertheless, the sum of normalized footprint results could still be environmentally irrelevant so long as it is not placed in an adequate context (Sleeswijk et al., 2008). For this reason, normalization is often followed by a weighting step in which the footprints of multiple impact categories are integrated into a single composite metric. We name this metric as composite footprint index *CFI*, which is equal to multiplying the normalized results with footprint weighting factor fwf_j for footprint j:

$$CFI = \sum_j nIPOF_j \times fwf_j \tag{3.7}$$

Unlike inventory weighting, footprint weighting in most cases cannot be replaced by a characterization approach given the difficulty of encompassing the full characteristics of divergent environmental impacts without the assistance of any subjective trade-off; with few exceptions, however, such as exergy-based characterization (Huysman et al., 2015). It means that in general value-based weighting is unavoidable when integrating a set of IPOFs into the CFI. This supports, to some extent, that a science communication intended to serve decisions must involve both facts and values (Dietz, 2013). The procedure for deriving weighting factors is beyond the scope of this chapter; see Ahlroth et al. (2011) for an overview.

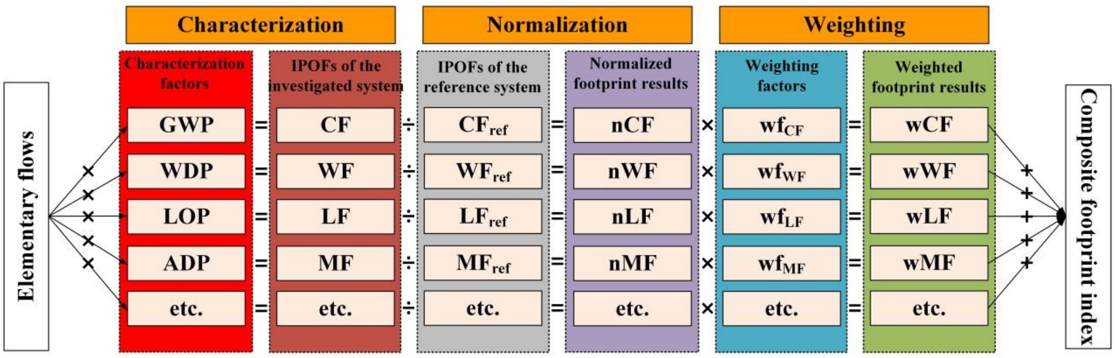

Figure 3.2. Schematic representation of the calculation and integration of a set of impact-oriented footprints under the characterization-normalization-weighting framework. It builds on the premise that all of the necessary data for inventory are sufficiently available. WDP: water depletion potential; LOP: land occupation potential.

Finally, as visualized in Figure 3.2, our proposal for the three-step framework makes a novel contribution to the area and is inherently different from the one that aims to bring together all footprints into LCA, because this framework can be operationalized without a life cycle approach, like for instance what is needed for an organization environmental footprint (OEF) (Fang and Heijungs, 2014b) and, in reverse, doing an LCA does not necessarily follow the inventory-characterization-normalization-weighting (ICNW) logic, like in LCA for EcoDesign (Karlsson and Luttropp, 2006).

3.4. Discussion

The investigation presented in this chapter offers new insights into the inventory aspect and characterization aspect of various footprinting methods, an important subject but being neglected by the majority of footprint practitioners and users. By dividing the selected footprints into two broad categories, namely the IVOFs and IPOFs, this chapter goes to lengths to show what distinguishes a footprint from another that has the same name but a different logic. There is admittedly no sharp boundary between a value-based inventory analysis and a science-based impact characterization due to gaps in scientific knowledge, and neither is there a sharp boundary between an inventory weighting and a footprint weighting. But like there is no such a boundary between dark and light, making the difference is still useful.

One reason for such ambiguity is the fact that subjective choices cannot be completely avoided in shaping an IPOF. The time horizon determined for GWP on which the CF_{clim} strongly depends is a typical example. Another reason is the lack of internationally agreed characterization modeling in some of the identified impact categories. For instance, it is found that even for the same abiotic resource the ADP can differ up to several orders of magnitude depending on the model chosen (Klinglmair et al., 2014). Moreover, resource depletion (including water depletion) is not always seen as a true environmental impact (Finkbeiner et al., 2014), nor the inherent characteristic of abiotic and biotic resources (Hauschild et al., 2013). Then the question comes up: what are the inherent characteristics that should be modeled for resource characterization? The reality is that in many cases resource flows do not have clear input and output characteristics (Udo de Haes, 2006).

In general, there is much more agreement on how to characterize emissions (e.g., GWP, ODP) than on how to characterize resource extractions. This is perhaps the foremost reason why the IPOFs are more advanced for emissions than for other forms of resources (e.g., land, water, material), for which the IVOFs have a considerably wide range of applications. The IVOF category of footprints provides a more practical way of measuring the pressure of resource use that is causing environmental impacts, and this is probably the initial purpose of footprint analysis. Although sometimes there are some simple conversions in the inventory phase of IVOP calculations, valuable physical information is maintained in relation to pressure exerted by the emission of wastes and extraction of resources. These merits, however, are obtained at the expense of undermining environmental relevance because assigned weighting factors are subject to artificial sequences that are almost unwarranted.

According to ISO (2006), footprint weighting is suggested as an option for further evaluation in the context of product LCA. One may easily extend this message to organizations and nations, in order to meet the non-professional demands (e.g., policy making, public communication) for a single-score, stand-alone metric for purposes of easy interpretation and trade-off analysis. In an attempt to standardize the integration of environmental footprints, our study has ascertained that integrating either the IVOFs or a mixture of the IVOFs and IPOFs is technically feasible but essentially meaningless. That is to say, it makes sense only if a set of carefully selected IPOFs are under consideration. Resembling the general procedure for LCIA, a three-step framework has been proposed for characterization, normalization and weighting of the IPOFs. Admittedly this is not much new for LCA experts, but we believe that it provides non-LCA experts with new insights into the fundamental nature of footprints and, more importantly, that it can serve as a unifying framework for discussions in communities that are quite disparate at the present moment, such as those of LCA, the water footprint, and the ecological footprint.

3.5. Conclusions

We herein come up with some conclusions that are supposed to fuel the ongoing discourse on a truly integrated footprint family. First, value-based weighting is hardly avoidable when integrating different footprint indicators into a single composite metric, because a thorough characterization model able to capture the full characteristics of related environmental impacts is virtually non-existent. Second, double counting and double weighting can nevertheless be avoided by the substitution of characterization factors for inventory weighting prior to footprint weighting. Third, the two categories of footprints identified offer two competing paradigms for the development of footprint indicators. Last, the ICNW logic could contribute to the standardization of footprint accounting—a more general framework that is inspired by the results of two decades of intense debate in the LCA community, but that can also be fruitful in life cycle-less contexts where there is no clear life cycle or even without an LCA. As a whole, the main value added of this chapter is the establishment of a unified framework for structuring, categorizing and integrating different footprints.

Accordingly, it should be emphasized that our proposal for restricting the integration practices to the IPOFs does not challenge the validity of the IVOFs, as the latter is appropriate for use in identifying the driving forces of environmental issues using understandable physical units, with the advantages of stimulating more forward-looking policy strategies and of reducing reliance on environmental governance at the end of treatment. Since both of the footprint categories have pros and cons, there is a need for more clarity on the applicability and limitations of each of them, as well as for an exploration of their potential synergies. Gaps in current knowledge, such as the unavailability of data and methods for inventory analysis and characterization modeling, and the uncertainty and subjectivity of normalization and weighting schemes, pose barriers to achieving that goal. In addition to the difficulties associated with footprinting integration, the classification issue is far from being settled as well. For instance, things get more complicated when it comes to the gray component of the WF_{class}, of which the quasi-characterization nature moves a bit away from our two-category framework. Responding to all these challenges that have to be confronted in proceeding with the development of footprint methodologies, we argue for multidisciplinary and interdisciplinary collaboration between footprint users and non-footprint users.

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