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The Waste Absorption Footprint (WAF): A methodological note on footprint calculations

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ABSTRACT

For a better understanding of human demand on the biosphere's capacity to assimilate wastes, this paper introduces a new footprint-based indicator, which is named the 'Waste Absorption Footprint' (WAF). The proposal of the WAF is inspired by the idea of building footprints on nature's multiple ecological functions. Within this framework, the WAF is built upon the waste absorptive capacity of the land and water area. This methodological approach is not confined to a particular waste product, but is able to include a variety of wastes generated by human activities. With this method anthropogenic emissions of wastes are translated into absorptive land and water areas. The results can be expressed in units of average hectares by scaling different land-use types in proportion to their relative absorptive capacity. The utility of the ecological footprint in sustainability evaluation can be greatly strengthened by combining the WAF to fully capture environmental effects induced by anthropogenic emissions of wastes. This paper also discusses the relationships of the WAF with other footprints and is intended to inform future debate on footprint accounting.

1. Introduction

The ecological footprint (EF) measures the amount of biologically productive land and water area required to support the demands of a population or an activity. Since its introduction by Rees and Wackernagel in the early 1990s (Rees, 1992; Wackernagel and Rees, 1996), the EF has been applied in various studies and analyses across geographical regions, spatial scales and time series (Bicknell et al., 1998; Van Vuuren and Smeets, 2000; Ferng, 2001; Bagliani et al., 2003; Wachernagel et al., 2004; Medved, 2006; Moran et al., 2008; Galli et al., 2012b). Analysts apply the EF to understand a population's or an activity's demand for the planet's limited capacity to provide a range of ecosystem goods and services. Given it is relatively easy to calculate, understand and communicate to the public, the EF has been widely acknowledged as one of the most effective evaluation tools to emerge in the sustainability debate.

As with all the tools that evaluate sustainability, the EF has also received a number of critiques (Van Den Bergh and Verbruggen, 1999; Moffatt, 2000; Ayres, 2000; Lenzen and Murray, 2001; Wiedmann and Lenzen, 2007; Fiala, 2008). One of the most heated debates emanates from the calculation of the footprint required to absorb wastes, generally known as the footprint of CO_2 sequestration in most footprint studies. Some of the most common arguments revolve around whether more land-use types than forests should be included (Siche et al., 2010), or whether other waste products (besides CO_2) should be taken into account (Walsh et al., 2009). Moreover, one problem with the carbon footprint, which has been pointed out more than once (Van Den Bergh and Verbruggen, 1999; Fiala, 2008), is that it accounts for more than 50% of the total footprint of most high and middle income nations. In a situation where CO_2 is considered the only waste product, human demand for waste absorption has already taken up half of the total allotment. Is that true?

Although this paper may not be the complete answer to such a yes-or-no question, it does provide a refined and thoughtful way to measure human demand for land-use types that assimilate wastes. This way of thinking is inspired by the idea to build footprints on nature's capacity to provide a variety rather than one single type of ecosystem services. Within this framework, the EF (except the carbon footprint) is in effect a footprint model based on the biologically productive capacity of the land and water area. The footprint model presented here, although also linked to area, is built upon the waste absorptive capacity of nature rather than its capacity to supply biological products. To avoid confusion with the EF, we name our concept the 'Waste Absorption Footprint' (WAF) – a measure of the demand of a given population or activity for the land and water area to absorb the wastes it generates.

The WAF and the EF are two equal footprint models within such a framework, as they are built upon nature's capacity to provide

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two different, but equally important, ecosystem services. Therefore, the WAF and the EF are regarded as two complementary methods, especially when they are applied to evaluate environmental sustainability. The utility of the EF in evaluating environmental sustainability can be largely increased by combining the WAF to fully capture the impacts of anthropogenic emissions of wastes.

2. Methodology

From the viewpoint of the WAF, the wastes generated by human activities require to be absorbed by natural ecosystems, such that the human demand for such waste absorptive capacity can be traced back to the land and water area that provides waste absorption services. Therefore, the WAF is defined as a measure of how much land and water area is required by a given population or activity to absorb the wastes it generates. This methodological approach is not confined to a particular waste product such as CO_2 emitted primarily from burning fossil fuels, but is able to include many other kinds of waste products released from human activities, such as surplus N or P resulting from the overuse of fertilizers for example. Yet, waste products that cannot be absorbed or broken down by any biological process are excluded from this accounting, such as heavy metals and their compounds. The WAF can also track human demand for waste absorption in terms of several land-use types, such as forest, cropland, grassland and inland water. This provides an alternative to assigning certain types of land use for waste absorption, such as forest for carbon sequestration as in the EF.

WAF models are recommended to be established according to specific categories or types of wastes. Different categories of wastes, such as those discharged into the air and to water, are commonly absorbed or broken down through different biological processes, and different types of wastes of the same category may have overlapping impacts on the environment. However, human demand for waste assimilation generally can be calculated by dividing the total amount of the released wastes by the absorptive capacity per hectare. Correspondingly, the Waste Absorption Capacity (WAC) can be calculated as the total amount of land available to absorb the wastes. All the results are expressed in units of hectares. They can be translated into national or global average hectares if conversion factors are available that scale different land-use types for their differences in waste absorptivity.

For any land use type, the footprint of waste absorption (WAF) of a country, in national hectares for example, is given by

$$\mathrm{WAF} = \frac{P}{\mathrm{NA}} \cdot \mathrm{AF} \tag{1}$$

where P is the amount of a waste product discharged; NA is the national average absorptivity for P; AF is the absorptivity factor for the land use type in question.

The capacity of waste absorption (WAC) of a country for any land use type is calculated as follows:

$$\mathrm{WAC} = A \cdot \mathrm{AF} \tag{2}$$

where A is the area available for a given land use type.

Here national hectares are defined as hectares of the absorptive land and water area with national average absorptivity. Absorptivity factors are applied to translate a specific area type (i.e. cropland, forest, grassland and inland water) into a national hectare by capturing the relative absorptivity among various land and water area types within a country. The absorption of a specific land type in a nation can also be translated into a world average hectare, if conversion factors are available that account for differences in absorptivity not only among various land types, but also between a national and the global average.

The choice of land use types in the WAF method is based on the consideration of natural ecosystems that have the capacity to provide waste absorption services. Cropland, forest, grassland and inland water are chosen as the four main land use types, while built-up land that is considered in the EF is excluded from the WAF accounting. However, it is difficult to define each land type according to the waste category or type it can assimilate or its capacity in absorbing a given waste product. In many cases a land type assimilates more than one of the waste products, and its absorptive capacity usually differs among different types of wastes. For example, forest is known as the most absorptive land type for CO_2, but it also assimilates SO_2 and NO_x. In addition, it accumulates nutrients and thus helps reduce non-point source pollution and eutrophication. Therefore, only when specific categories or types of wastes are determined can land use types be adequately defined.

From the above equations, we can see that there are several important questions that need to be resolved in a national WAF calculation: (1) the amount of wastes released into different land-use types; (2) the uptake rates of different land-use types for the wastes; (3) the absorptive factors. The last two questions are closely related to the differences in waste absorptive capacity among different land use types. The calculation of such differences requires to be undertaken at a national scale on a case-by-case basis, and depends on adequate data sets that derive from field research. For the first question, we put forward some possible solutions using the examples of CO_2 and its equivalents below.

As the WAF and the WAC are expressed in the same unit, human demand for waste absorption can be compared directly to absorptive capacity at a local, national or even global scale, from which environmental sustainability of a local area, a nation or the globe, in terms of waste assimilation, can be estimated. If human demand exceeds nature's absorptive capacity, it shows that the environment has been developed in an unsustainable way with a condition of waste absorption deficit. Conversely, if available capacity surpasses human demand on absorptivity, a waste absorption reserve occurs, indicating that the environment currently meets the minimum criteria for sustainability.

The way the WAF is calculated is elaborated in more detail below where CO_2 and its equivalents, surplus N and P are taken as examples.

For CO_2 or its equivalents emitted to the air, the footprint model can be built upon the capacity of the land and water area to sequester carbon. The carbon footprint (tentatively named here) represents the area appropriated for carbon sequestration while the carbon capacity represents the land available for carbon sequestration. Forest is the most absorptive of all the land types, as nearly half of terrestrial carbon is stored in forests (Dixon et al., 1994) and 70% of carbon exchange between the atmosphere and terrestrial vegetation occurs in forests (Schroeder, 1992). Grassland is second to forest, which accounts for about 25% of the terrestrial carbon sink (De Fries et al., 1999). Wetland, as one type of inland water, is another carbon pool where the carbon storage surpasses that of cropland (Parish and Looi, 1999).

For any of the four land use types, the carbon footprint (WAF_C) of a country, in national hectares, is given by

$$\mathrm{WAF_C} = \frac{P_\mathrm{C}}{\mathrm{NA_C}} \cdot \mathrm{AF_C} \tag{3}$$

where P_C is the amount of carbon emitted in a given year (excluding those sequestrated by oceans); $\mathrm{NA_C}$ is the annual national average absorptivity for carbon; $\mathrm{AF_C}$ is the carbon absorptivity factor for the land use type in question.

A country's carbon capacity ($\mathrm{WAC_C}$) for the given land use type is calculated as follows:

$$\mathrm{WAC_C} = A_\mathrm{C} \cdot \mathrm{AF_C} \tag{4}$$

where A_C is the area available of a given land use type.

It might seem difficult to determine the amounts of CO_2 or its equivalents going into different land use types, as gas emissions exchange frequently in the atmosphere, the ocean and among different land-use types. However, we put forward some possible solutions suggesting that their rationality and practicability will need further discussion. One of the solutions is that we allocate the amount of carbon emissions (excluding those absorbed in oceans) among different land-use types of a country according to their differences in the annual amount of carbon sequestration. Then we can translate the carbon emissions allocated to each land type into the amount of national average land needed to store them using Eq. (3). Another solution can be realized under the assumption that for a given country, after subtracting the amount sequestered in oceans from the total, the remaining carbon will be preferentially stored in the land-use types with high uptake amounts. Therefore, different land-use types can be calculated in a descending order according to their differences in annual carbon uptake. The calculation will be finished if carbon emissions are fully assimilated by the various land-use types within the territory of the nation. If not, we can estimate how much national average land is required for sequestrating the rest of the carbon. The results obtained from the first step can be translated into national hectares using Eq. (3) and calculated as the carbon footprint of the nation plus the results from the second step.

For surplus N or P released into the environment, the footprint model is quite similar to that for CO_2 or its equivalents, which can be built upon the capacity of the land and water area to assimilate N or P. Similar questions also need to be resolved before the nitrogen or phosphorus footprint (again named temporarily here) is calculated, such as determining the amount of N or P released into different land-use types. Some researchers have tried to estimate the transport of N or P among different land-use types. For instance, Wackernagel et al. (1999) suggested that 10% of the arable area in their case study area give approximately 70% retention of nitrogen. Yet, appropriation of different ecological spaces caused by surplus N or P release can only be accurately described based on field research results about the transport mechanisms of N or P across various land-use types. As is already evident, the WAF calculation requires a large amount of data as a basic condition.

In some cases, however, waste products that are released into a specific land-use type cause far more concern when a specified environmental problem is targeted. For those wastes, footprint models can be built based on the capacity of the given land type to provide absorption services. Take surplus N or P discharged into water as an example, which is considered one of the most important reasons for the decline in water quality. The nitrogen or phosphorus footprint represents appropriated absorptivity, and the nitrogen or phosphorus capacity represents the availability of absorptive water area. For the given land type, inland water, the nitrogen footprint (WAF_N) or the phosphorus footprint (WAF_P) of a country, in national hectares, is given by

$$WAF_N = \frac{P_N}{NA_N} \cdot AF_N \quad (5)$$

$$WAF_P = \frac{P_P}{NA_P} \cdot AF_P \quad (6)$$

where P_N or P_P is the amount of N or P released or transported into the water; NA_N or NA_P is the national average absorptivity of inland water for N or P; and AF_N or AF_P is the N or P absorptivity factor for inland water.

A country's nitrogen capacity (WAC_N) or phosphorus capacity (WAC_P) for inland water is calculated as follows:

$$WAC_N = A_N \cdot AF_N \quad (7)$$

$$WAC_P = A_P \cdot AF_P \quad (8)$$

where A_N or A_P is the water area available for N or P absorption.

After elaborating the WAF calculation based on specific waste products, we find there is a major problem of how to determine the relationship among footprints of different waste products. Here we present a very preliminary proposal. Its applicability largely depends on the actual situation. For wastes that are in the same category and have an accumulative impact on the environment, we recommend that the total amount of their footprints be taken as the WAF of that category. For instance, the sum of the footprints of CO_2 and its equivalents can be regarded as the WAF of the air pollutants that generate the greenhouse effect. For wastes that are in the same category and have an overlapping effect on the environment, we suggest that the maximum value of their footprints be taken as the WAF of that category. For example, the larger of the nitrogen or phosphorus footprints for inland water can be considered as the WAF of the wastes that cause water quality decline, provided that other wastes discharged into the water are not taken into account.

However, there is a further complication in which wastes of different categories enter into the same environmental media, but require different assimilative mechanisms. For example, emitted carbon and surplus nutrients might enter into the same environmental media such as cropland, but they would be absorbed through totally different biological processes. In such a situation, the environmental media in effect provide two different kinds of waste absorption services: carbon sequestration and nutrient removal (Costanza et al., 1997). The WAF can thus be further categorized into footprints based on different waste absorption services. In this sense, the WAF of the CO_2 and its equivalents can be referred to as the 'carbon sequestration footprint', while the WAF of the surplus N and P can be named the 'nutrient removal footprint'. These two footprint models are as equal as the EF (excluding the carbon footprint) within the framework of building footprints on multiple ecological functions. How to deal with their relationships and to explore their joint use will be elaborated upon in the following section.

3. Discussion

The WAF method builds on the capacity of the land and water area to assimilate waste products, measuring human demand for waste absorption services and revealing anthropogenic influences on the environment. However, there are several key questions that need to be further explored, especially when the proposed method is applied to complex situations. For example, how can the WAF of waste products of the same category be calculated when they are assimilated by different land-use types? Several possible solutions have been provided for the calculation of the footprints of CO_2 and its equivalents, but accounting methods for other waste products are still largely unexplored. Then, how does one determine the relationship among WAFs of different waste categories when the environmental media provide more than one type of waste absorption service? Additionally, how do we combine the use of the WAF with footprints based on other ecological functions such as the bioproductivity-based footprint?

The proposal of the WAF is inspired by the idea of categorizing footprints according to ecosystem service types they are designed to measure. Within this framework, footprints can first be divided into two types, although it must be noted that Costanza et al. (1997) grouped ecosystem services into 17 major categories. The first footprint type is based on nature's biologically productive capacity and is utilized to measure human demand for the bio-product provision service. This footprint model, equivalent to the EF (except the footprint of CO_2 assimilation), can be labeled the 'bio-product provision footprint'. The other is the WAF. As is pointed out in Section 2, the WAF can be further categorized when the environmental media provide different kinds of waste absorption services. Given the two types of waste absorption services considered in this paper, the WAF can be further divided into the 'carbon sequestration footprint' and the 'nutrient removal footprint'. So far we can see that there are at least three kinds of footprints that can be built upon nature's capacity to provide ecosystem services.

Within such a framework, the three footprint models are mutually equal, measuring three important aspects of environmental sustainability. For the evaluation of any one aspect, the corresponding model can be applied independently and the conclusions drawn from it can stand alone. However, when it comes to integrated environmental concerns, these footprints can serve as complementary methods to each other. Their joint use can greatly enhance the comprehensiveness and effectiveness of the footprint method in evaluating environmental sustainability. Combining their use can be realized through the integration within the 'Footprint Family' framework which offers a suite of indicators for sustainability assessment (Galli et al., 2012a). There is also a possibility of creating a more composite indicator because all the footprints are linked to area within the framework proposed in this paper. The con-joint use of these footprints will require the integration of their area-based results, which relies on conversion factors that account for differences in the supply capacity of the environment among different ecosystem services.

Here, one might question the necessity of using the footprint, an aggregated area-based indicator, to measure human appropriation of nature's capacity to provide ecosystem services and then make judgments on environmental sustainability. It must be admitted that, in some cases, it is more useful to abandon composite indicators and instead look directly at the individual and most important elements. However, compound indicators reflect complex interactions and enable us to make comparative generalizations across time and space. They are often essential in decision-making processes (Pulselli et al., 2008) and have become important as educational and "big picture" contextualizing tools among many current users (Global Footprint Network, 2008).

Take the WAF as an example. The amounts of waste products released into the environment cannot be used effectively to indicate the environmental effects caused by them, although they can reflect the intensity of anthropogenic emissions to a certain extent. However, after being converted to land areas using the WAF method, different waste products can more easily be compared to each other and their interactions in influencing the environment can more effectively be noted. The conversion also makes it possible to compare human demand with nature's capacity and enables us to make judgments on the sustainability of the environment, which is important for decision-making in environmental management. Further, if the WAF can be integrated with footprints based on other ecological functions in an appropriate way, the footprint method will be enhanced to incorporate more human demands for ecosystem services and to capture more aspects of environmental sustainability. However, the WAF also has apparent weaknesses For instance, the calculation of conversion factors requires a great quantity of data at a national scale that may not be consistently available nor easy to be collected. In addition, the amounts of wastes released into different land-use types are calculated relying heavily on assumptions and estimations. All of these will to some extent add difficulties to the worldwide coverage of WAF accounting.

The relationship of the WAF with other footprint-based indicators is also an interesting issue. One of them, named the 'carbon footprint', is used by some organizations to refer to the quantities of carbon dioxide emissions associated with an activity, process, or product (BP, 2008; Wiedmann and Minx, 2008). When it is used in the EF, this term is synonymous with demand on the land area for CO_2 sequestration. This 'carbon footprint' is commonly measured in tons of carbon dioxide equivalents, while in EF accounts it is an area-based measure after being translated into global hectares. From this perspective, the WAF is quite different from this 'carbon footprint', as the 'carbon sequestration footprint' is also an area-based indicator expressed in units of hectares. Therefore, this 'carbon footprint' actually forms a part of the 'carbon sequestration footprint'. Besides, human demand for carbon sequestration can be compared to nature's absorptive capacity from which the impact of climate change can be estimated. Additional impact assessment models that are needed in the 'carbon footprint' are not necessarily required in the WAF method.

Similar relationships exist between the WAF and the 'nitrogen footprint' which provides information on how individual and collective actions result in the loss of N to the environment (Leach et al., 2012). This N calculator focuses on food and energy consumption and expresses its results in kilograms of N per capita. The 'nutrient removal footprint', in contrast, is not limited to particular human activities. Nitrogen released into the environment can be translated into hectares with the help of conversion factors. In this sense, the 'nitrogen footprint' is merely a part of the 'nutrient removal footprint'. Additionally, the 'nitrogen footprint' has not yet linked N losses to their environmental impacts, while the comparison between human demand and natural supply in the WAF method can effectively reveal human induced effects on the environment.

Another footprint approach came with the development of the 'water footprint', which most commonly refers to a measurement of total volume of water consumed (Hoekstra and Chapagain, 2007). The 'water footprint', unlike the 'carbon footprint', is not a part of the EF, and is only indirectly accounted for in the EF analysis (Kitzes and Wackernagel, 2009). Given the difficulty in grounding the footprint of fresh water, the volume water has become the methodological basis for this footprint approach instead of land area. In this respect, the WAF differs significantly from the 'water footprint' as it is based on the concept of limitation of the availability of ecosystem services in a given area. However, the WAF method provides another way to ground the 'water footprint', even if someone has already tried to calculate the 'water footprint' based on the area of catchments or recharge zones needed to supply a given quantity of water (Luck et al., 2001; Stoeglehner et al., 2011). Within the new framework, the footprint used to measure human demand for water supply can be built on the capacity of the land and water area to provide fresh water. This footprint model can be referred to as the 'water supply footprint', another type of footprint based on nature's ecological functions. Its con-joint use with the other three footprints can cover another important aspect of environmental sustainability and greatly increase the validity of the footprint method in sustainability assessment.

4. Conclusions

This paper offers another way to measure human demand for the planet's capacity to absorb human generated wastes by introducing the 'Waste Absorption Footprint' (WAF). The proposed method presents waste absorption separately from the EF approach, and builds on the land and water area's capacity to assimilate the waste. Such a disaggregated method is not merely an improvement in the measurement of waste absorption, but it also opens a door for other types of ecosystem services to be included into footprint accounts. Under this methodological approach, we wonder how large the carbon footprint is and what percentage it accounts for. Although the exact answer cannot be found in this paper, we can expect that future research will answer these questions using the proposed method. Regardless of the outcome, the current status of the carbon footprint will certainly be challenged. Future research is also expected to pay attention to footprints based on different ecological functions and their inter-relationships.

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