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An Axiomatic Foundation of the Ecological Footprint

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Abstract

The objective of this paper is to provide an axiomatic foundation to the ecological footprint developed and refined by the authors in the Global Footprint Network, among others. For this purpose, five axioms are proposed which represent general properties any ecological footprint measure should fulfill. We show that an index exists which is unique up to a coefficient to be chosen arbitrarily. As an implication, footprints have to be measured on a ratio scale. This result supports the conventional unit of measurement (land area) which itself is represented by a ratio scale. In this respect, our index differs from the compound-based ecological footprint index in which the norm is missing and, therefore, it is implicitly set equal to one. Apart from that we find, as the most important result, that the ad-hoc design of the commonly applied ecological footprint index has been given an axiomatic foundation.

JEL classification: Q13, Q41, Q43, C43

Keywords: Ecological Footprint Index, Axiomatic Foundation, Measurement Theory, Overshoot Day, Sustainable Welfare

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1 Introduction

Each year, the Global Footprint Network is announcing the Earth Overshoot Day prominently reported worldwide in the media. However, there is no reason to celebrate this anniversary, nor is it fixed by date. Rather, it marks the day in the year when mankind has demanded the entire ecosystem services our planet is annually providing to satisfy human needs. Ever since the overshoot day has been computed for the first time, the data show a permanent backward shift in time. It means that the services of the ecosystem to support consumption activities as well as the the absorption of waste products are used up ever earlier in the course of the year. In a sense, from then on the earth is running into an ecological disaster. The respective data are not only available on the global level but also on the national, indicating a much more eco-friendly use of resources in the less developed countries than in the developed ones. For instance, in 2018 the Overshoot Day for Germany has been May, 2, compared to Aug, 1 for the world (Global Footprint Network, 2018a, 2018b).

Not surprisingly, there is a serious debate on how the overshoot day exactly should be determined and what kind of measure should be applied. Literally, over the last few decades, various indicators have been proposed in the literature to measure the exertion of renewable natural resources and, consequently, the pressure put on the ecosystem by human activity, in particular by means of land area appropriated. Among the group of Ecological Footprint Indices typically labelled as the 'footprint family' are the sustainable process index (Krotscheck/Narodoslawsky, 1996, Sandholzer/Narodoslawsky, 2007, Stöglehner/Narodoslawsky, 2012) and the component-based ecological footprint (Simmons/Lewis/Barrett, 2000) as a life-cycle assessment of economic activities, alongside a number of complementary footprint indicators related to different environmental media¹ such as the carbon, water or nitrogen footprint (Galli et al., 2012, Čuček et. al., 2012, Fang et. al., 2014, and others). However, over the last years, the focus has been put on one particular index which especially is being applied in statistical cross-country/cross-regional comparative research, and thus has been prevailed: the compound-based ecological footprint (Wackernagel/Monfreda, 2004, Galli et al., 2016), in short referred to as '*the ecological footprint*'; together with the biocapacity index as a complement.

¹In this context, the footprint index indicates the pressure exerted by human activity on the respective environment medium or via the respective pollutant.

Originating from the pioneer works from WACKERNAGEL and REES (i.a. Rees, 1992, Wackernagel/Rees, 1996, Wackernagel et al., 1999), the concept, methodology, and application of ecological footprinting has been continuously refined and improved, especially by the Global Footprint Network (among many others, see Bicknell et al., 1998, Ferguson, 1999, Venetoulis/Talberth, 2008, Wang/Bian, 2008, Galli et al., 2011, 2012, 2016, Borucke et al., 2013, Collins/Flynn, 2015, and Lin et al., 2018). The common methodology is to compare the supply of and demand for ecological goods and ecosystem services in terms of units of land area appropriated to annually regenerate and provide these goods and services. For this purpose, *global hectares* have been introduced as a common unit of measure taking into account differences in the ecological productivity in land types (converting world-average hectares into global hectares through *equivalence factors*) as well as across nations of the same land type (converting nation-specific hectares into world-average hectares through *yield factors*).² While biocapacity depicts the supply side, i.e. the 'ecological budget', the demand human populations and activities place on the biosphere is measured by the ecological footprint. Comparing annual supply of and demand for natural resources and ecosystem services finally enables an assessment of a country's or region's ecological overshoot, i.e. the ecological deficit due to overexploitation of resources and accumulation of waste (Wackernagel/Monfreda, 2004). In this respect, the overshoot day is simply found as the ratio between the footprint index and the biocapacity index times 365 (measured in day units).

With the initiative of the Earth Overshoot Day, as said, the Global Footprint Network has found a very effective means to communicate its results in the public. Expressing the framework of an annual time line has struck a chord with large parts of the population in the industrialized world. Given that the date is moving backwards every year, the demand for more sustainable consumer lifestyles and structural change towards a low-carbon global economy becomes all the more compelling (Global Footprint Network, 2018a, 2018b).

However, the ecological footprint concept has also been exposed to severe criticism regarding its applicability, methodology, and policy implications (see van den Bergh/Verbruggen,

²The most recent methodology even accounts for land productivity differences in time by extending the unit of measure to *constant global hectares* through a *world-average intertemporal yield factor*, expressed with reference to a selected base year. This step is aimed to avoid difficulties of interpretation in intertemporal comparison. (Borucke et al., 2013)

1999, van den Bergh/Grazi, 2013, and Galli et al., 2016, among many others). One of the major concerns relates to the identification of the expected characteristics of the ecological footprint and biocapacity measures as well as to the accuracy of the measurement scheme (Galli et al., 2016). Indeed, these indices have been designed in a more or less ad-hoc fashion way and have not been further analyzed yet with respect to their mathematical foundations, at least from an axiomatic view - in contrast to the majority of economic indices such like price indices or indices of economic inequality which have been characterized axiomatically.

The lack of an axiomatic foundation of such kind is all the more surprising considering that data on the ecological footprint is recently collected and utilized in the official statistics of various international organizations. Moreover, ecological footprinting has already been included in those institutions' methodologies on environment statistics as an indicator for sustainable land use (see, for instance, OECD, 2008, UNEP, 2010, UN Statistics Division, 2013, 2018). As a consequence, the family of ecological footprint indices still needs to be reviewed with respect to whether the explicit and implicit properties must be considered as appropriate.

This paper therefore intends to provide an axiomatic approach to the ecological footprint concept. We define a set of fundamental axioms representing general properties any footprint measure should fulfill according to the properties considered appropriate. The advantage of this approach lies in the proposition of a few stylized facts on which there is a clear idea of how the index should respond. But most importantly, once the formula of the index has been determined it can be applied to any real-world situation, irrespective of the particular values the independent variables may take. As a result we find that a unique index exists which is fully meeting the proposed axiom system. Subsequently, its features are discussed in detail.

The paper is structured as follows: In section 2, some possible properties of a footprint index are emphasized and transferred into an axiom system which is to be fulfilled. In section 3, we propose an ecological footprint measure based on these axioms before we try to compare it to the indices already existing in the literature in section 4. Finally, the paper is concluded with a discussion in section 5.

2 The Axiom Set

In this section, we are developing a system of axioms for the characterization of the ecological footprint index (EF). Naturally, the axiom system proposed should comprise properties generally accepted in the literature. In particular, it refers to a specific type of product and of land area use (with given bioproductivity), hence a so-called footprint component is a constitutional part of the composite measure.³ First, we will give a general definition.

Definition 1. *Let $D = \mathbb{R}_+^5$ be a set of ecological states, where $x = (C_n, Y_n, A_n, Y_r, A_r) \in D$ is a vector comprising national product consumption C_n , national product output Y_n , national land area A_n appropriated, product output in the rest of the world Y_r , and land area used in the rest of the world A_r , each for a given type of product and for a given land area type. Then, the ecological footprint index is a mapping:*

$$f : D \mapsto \mathbb{R}_+, \quad x \mapsto f(x)$$

■

with the meaning that the ecological footprint of state x is bigger than that of y if $f(x) > f(y)$.

The function f should satisfy the following set of axioms.

Axiom 1 (Monotonicity). *The function f is strictly increasing in C_n :*

$$f(\underline{C}_n, Y_n, A_n, Y_r, A_r) < f(\overline{C}_n, Y_n, A_n, Y_r, A_r) \quad \text{for } \underline{C}_n < \overline{C}_n$$

■

Remark 1. It seems to be natural to assume that the ecological footprint index should take higher values if a country's product consumption goes up, all other things equal. This property is evident and perfectly in line with what an EF should measure from the view of sustainable land area use. It indicates that there is an higher demand on renewable natural resources to supporting human activity.

³The issue of characterizing functions for the aggregation of footprint components over the various product types as well as area types will be discussed in a paper to follow.

Axiom 2 (Proportionality to Consumption). *The index is directly proportional to a country's product consumption, all other things equal.*

$$f(\lambda C_n, Y_n, A_n, Y_r, A_r) = \lambda f(C_n, Y_n, A_n, Y_r, A_r) \quad \text{for } \lambda > 0$$

■

Remark 2. In our opinion, this axiom is reasonable. If the world average yield does not change a country's footprint in terms of the land area appropriated, its demand on the carrying capacity of the ecological system is directly proportional to its amount of consumption.

Axiom 3 (Proportionality to Land Area Use). *The index is directly proportional to the world land area appropriated, all other things equal.*

$$f(C_n, Y_n, \lambda A_n, Y_r, \lambda A_r) = \lambda f(C_n, Y_n, A_n, Y_r, A_r) \quad \text{for } \lambda > 0$$

■

Remark 3. This axiom in our view is perfectly in line with what the spirit of the ecological footprint concept is suggesting. All other things equal, the index is directly proportional to the worldwide use of land area because demand on the carrying capacity of the ecological world system to satisfy the same consumption needs is going up proportionally.

Axiom 4 (Commensurability). *An equal proportional change in the world land area and the world production does not change the value of the index*

$$f(C_n, \lambda Y_n, \lambda A_n, \lambda Y_r, \lambda A_r) = f(C_n, Y_n, A_n, Y_r, A_r) \quad \text{for } \lambda > 0$$

■

Remark 4. Axiom 4 is proposing that the ecological footprint should not respond to an equal proportional change in world area use and world production, all other things equal. In this case, world average product yield remains the same for any given amount of national consumption. It means that a country's product consumption requires the same share of the earth's ecological resources, such that the value of its foot print should remain constant.

Axiom 5 (Compensability). *A shift in the land area use between countries as well as a shift in production output between countries does not change the value of the index. More precisely, the footprint remains unchanged if a change ΔY in national output produced is offset by an equal and opposite change $-\Delta Y$ in output produced in the rest of the world, and, at the same time, a change in the national land area use ΔA is offset by a opposite change in the land use $-\Delta A$ in the rest of the world:*

$$f(C_n, Y_n + \Delta Y, A_n + \Delta A, Y_r - \Delta Y, A_r - \Delta A) = f(C_n, Y_n, A_n, Y_r, A_r)$$

for $Y_n \geq -\Delta Y \wedge Y_r \geq \Delta Y \wedge A_n \geq -\Delta A \wedge A_r \geq \Delta A$

■

Remark 5. This axiom is related to the previous axiom, but with the distinction that in this case the world average product yield stays the same through offsetting changes in national production and national land use by appropriate changes in the rest of the world. So, from a global view, the demand of national product consumption on the worldwide natural resources remains the same. The only difference is the absence of any scale effect in world production and world land area. However, since such scale effects should not affect the index anyway according to Axiom 4 the same line of reasoning as before applies here.

In the following section, we will derive an index satisfying the entire axiom system simultaneously.

3 Existence and Uniqueness of the Ecological Footprint Index

Let us now state the following proposition.

Theorem (Existence and Uniqueness). *Axioms 1 through 5 characterize the following unique index up to a strictly positive arbitrary coefficient which is $f(1, 1, 1, 0, 0) > 0$:*

$$\begin{aligned}
EF(C_n, Y_n, A_n, Y_r, A_r) &:= \frac{C_n}{Y_n + Y_r} \cdot (A_n + A_r) f(1, 1, 1, 0, 0) \\
&= \frac{C_n}{Y_w} \cdot A_w f(1, 1, 1, 0, 0) \\
&= \frac{C_n}{Y_w/A_w} f(1, 1, 1, 0, 0) \\
&= \frac{C_n}{Y_n/A_n} \cdot \frac{Y_n/A_n}{Y_w/A_w} f(1, 1, 1, 0, 0)
\end{aligned}$$

with $Y_w := Y_n + Y_r$ and $A_w := A_n + A_r$

Proof. See Appendix. □

This proposition states that there exists an index which meets the axiom system and that the index is unique up to a constant factor $f(1, 1, 1, 0, 0)$ which can be chosen arbitrarily from \mathbb{R}_+ the positive set of real numbers. This factor gives the unit of the scale, i.e. the norm.

What is the meaning of the index stated above? The functional form of the index can be read in different ways according to the sequence of equations stated in the existence theorem in section 3 which are equivalent. First, it may be interpreted as the land area A_w appropriated to provide a country's share of consumption on world production, C_n/Y_w . Secondly, the index gives the demand of national consumption on world average product yield. If national product consumption is equal to world production, a country is demanding the entire land area globally available. Put differently, the index indicates how much land area of world average productivity is appropriated to satisfy a country's consumption needs. Finally, the index is measuring a country's consumption share on production in terms of the land area used in that country weighted by the ratio between the national product yield and the world average product yield.

The scale of the index is determined as a ratio scale since any transformation of the scale by an arbitrary factor is feasible. In this case, the ratio of scale values remains invariant. This result seems reasonable, in particular, if we keep in mind that the index is measured in units of land area, and land area itself, by measurement theory, is represented by a ratio scale. Hence, if we apply a feasible transformation of the scale by a given factor, the index

is scaled up by the same factor. Therefore, the information content of the scale is given by the ratio between any two values. The absolute magnitude of the index is meaningless. This property of the index can easily be proved again by inspection of Axiom 3, if we take λ as a feasible transformation of the land area scale.

4 Implications for the Measurement of Ecological Footprints

The index found above turns out to be almost the same as given in WACKERNAGEL ET AL. (1999) (as well as in the subsequent literature referred to in the introduction), apart from the arbitrary coefficient. It is in fact defining an index component of the composite measure, which is the compound based ecological footprint index as mentioned. In the following we will discuss it in more detail.

Setting $f(1, 1, 1, 0, 0)$ to 1 and noting that yield γ is equal to Y_w/A_w and that $C_n = Y_n - XS_n$ with national production Y_n and national net exports XS_n one gets:

$$EF = \frac{(Y_n - XS_n)}{\gamma}$$

Therefore, if a country is a net exporter, i.e. $XS > 0$, its ecological footprint is decreasing (increasing) if exports XS are going up (down). An equivalent line of reasoning holds if a country is a net importer, i.e. $XS < 0$.

This index represents a footprint component in the compound-based ecological footprint index EF_C which, in its reduced form, reads:

$$EF_C = \sum_{i=1}^N FC_i \cdot EQF_i$$

where FC_i is the footprint component of sector i ($i = 1, \dots, N$) determined by

$$FC_i = \frac{C_i}{\gamma_{w_i}}$$

with C_i denoting annual domestic consumption of products in sector i , γ_{w_i} being the world-average yield of that sector, i.e. Y_{w_i}/A_{w_i} , and EQF_i is the equivalence factor of land area type i .

The compound-based ecological footprint index is the weighted sum over all footprint components according to the specific land area types respective sectors. Each sector component measures the land area of world average productivity appropriated to consumption. The equivalence factors provide the weight scheme for aggregation by transforming specific land area types onto a common scale, i.e. global hectares (gha). Yet, we should not get the illusion of having an absolute measure which only originates from the missing norm.

5 Concluding Remarks

The objective of this paper has been to establish an axiomatic foundation to the concept of the ecological footprint index. We first identified the characteristics of generally accepted footprint indices and discussed their methodologies. We then proposed five axioms which we considered appropriate for constructing a mathematical formula for footprint indices in general. It has been shown that there exists an index, measured on a ratio scale. Furthermore, its functional form has been determined.

Surprisingly, the index found is quite similar to the compound-based ecological footprint index. With respect to empirical applications, this might be considered as important because the most prominently used index has now been given a theoretical foundation. The main difference lies in the norm of the scale which is implicitly set equal to one in the latter but which, in fact, can arbitrarily take any positive value. That finding is reasonable because the footprint index is measured in terms of land area units which, by measurement theory, itself is represented by a ratio scale. Hence, absolute values are meaningless. With respect to the trade issue discussed in the literature, the incorporation of imports and exports in our measure is assured for as well.

The same arguing in principle holds for the Overshoot Day. However, since that measure is given by the ratio of the footprint index and the biocapacity index, the Overshoot Day is invariant to a feasible and equal transformation of both of the scales. A formal

analysis is a scope of future research. Another remaining issue would be characterizing the composite measure, in particular it will have to be analyzed whether a common scale is required at all for the aggregation procedure.

Appendix

Proof of the Existence and Uniqueness Theorem. First, it can be easily seen that $EF(C_n, Y_n, A_n, Y_r, A_r) := \frac{C_n}{Y_n + Y_r} \cdot (A_n + A_r) f(1, 1, 1, 0, 0)$, with $f(1, 1, 1, 0, 0) > 0$ satisfies axioms 1 to 5. This is shown by a straightforward calculation after substituting EF for f in the axioms, which proves the existence of an index that satisfies the given axioms.

It remains to show the uniqueness of the index. For this we will derive EF from axioms 2 to 5.

By axiom 5 we have with $\Delta Y = Y_r$ and $\Delta A = A_r$

$$\begin{aligned} f(C_n, Y_n, A_n, Y_r, A_r) &= f(C_n, Y_n + \Delta Y, A_n + \Delta A, Y_r - \Delta Y, A_r - \Delta A) \\ &= f(C_n, Y_n + Y_r, A_n + A_r, 0, 0) \end{aligned}$$

Continuing by setting $Y_w := Y_n + Y_r$ and $A_w := A_n + A_r$ and applying axiom 2 with $\lambda = 1/C_n$ we obtain:

$$\begin{aligned} f(1, Y_w, A_w, 0, 0) &= \frac{1}{C_n} f(C_n, Y_w, A_w, 0, 0) \\ \Leftrightarrow f(C_n, Y_w, A_w, 0, 0) &= C_n f(1, Y_w, A_w, 0, 0) \end{aligned}$$

Similarly axiom 3 with $\lambda = 1/Y_w$ applied to the RHS of the last equation and rearranging yields

$$\begin{aligned} C_n f(1, 1, A_w, 0, 0) &= C_n Y_w f(1, Y_w, A_w, 0, 0) \\ \Leftrightarrow C_n f(1, Y_w, A_w, 0, 0) &= \frac{C_n}{Y_w} \cdot f(1, 1, A_w, 0, 0) \\ \Leftrightarrow f(C_n, Y_w, A_w, 0, 0) &= \frac{C_n}{Y_w} \cdot f(1, 1, A_w, 0, 0) \end{aligned}$$

Finally, using axiom 4 with $\lambda = 1/A_w$ and rearranging analogously to the last proof step

one finally gets

$$f(C_n, Y_w, A_w, 0, 0) = \frac{C_n}{Y_w} A_w f(1, 1, 1, 0, 0)$$

Comparing this to the first equation, we get

$$f(C_n, Y_n, A_n, Y_r, A_r) = \frac{C_n}{Y_w} A_w f(1, 1, 1, 0, 0)$$

Clearly, if this is to be a monotonically increasing function in C_n as stated by axiom 1, $f(1, 1, 1, 0, 0)$ has to be positive (Y_w, A_w being positive).

Thus, axioms 1 through 5 define the unique index $EF(C_n, Y_n, A_n, Y_r, A_r)$ up to a multiplicative factor $f(1, 1, 1, 0, 0) > 0$. \square

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