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ECOIND-1914; No. of Pages 11
ARTICLE IN PRESS
Ecological Indicators xxx (2014) xxx–xxx
Contents lists available at ScienceDirect
Ecological Indicators
journal homepage: www.elsevier.com/locate/ecolind

Letter to the Editor

Footprint facts and fallacies: A response to Giampietro and Saltelli (2014) "Footprints to Nowhere"

ARTICLE INFO

Keywords:
Ecological footprint
Biocapacity
Criticism
Methodology
Sustainability metric

ABSTRACT

The Ecological Footprint is a resource accounting tool that tracks human demand on the Earth's biological resource flows, and compares it with the Earth's capacity to generate these same flows. Critical discussion of Ecological Footprint accounting contributes to the ongoing development of its methodology, comprehensibility and policy relevance as a science-based metric. Giampietro and Saltelli's recent critical article provides an opportunity to address some fundamental misunderstandings about the metric, including the research question it seeks to address, the methodology used to calculate Footprint and biocapacity results, and what the results do and do not imply. Contrary to their criticisms, it is shown that the Footprint reflects the productivity of actual rather than hypothetical ecosystems, does not claim to be a comprehensive measure of sustainability, and is not prescriptive about trade practices nor any other policy decisions, including how to respond to the finding that the world is in ecological overshoot. Despite acknowledged current limitations of Ecological Footprint accounting, including that the calculation methodology, in exercising scientific caution, might somewhat underestimate the challenge facing humanity, Giampietro and Saltelli's criticism that the results are reassuring and encourage complacency appears to be unwarranted. In addition, it is argued that the continued refinement of the metric as new scientific findings and improved data sets become available is not, as Giampietro and Saltelli suggest, a liability of the measure, but instead a strength that increases both its value as an indicator of the magnitude of human pressure on global ecosystems, and its policy relevance.

1. Introduction

In their critique of Ecological Footprint accounting, Giampietro and Saltelli (2014) argue that the Ecological Footprint "*does not serve a meaningful discussion on the modeling of sustainability*" and that despite this fault, it has become widely used across the planet because it is "*media-friendly*," "*reassuring*" and generates complacency rather than, presumably, a sense of urgency *about "man's pressure on the planet and its ecosystems."* The authors support their strong claim through several lines of argument: that the Footprint does not measure what it claims to be measuring; that the metric is computationally "*laborious*" while at the same time "*fragile*;" that the most widely reported finding associated with Ecological Footprint accounting – that human demand on global ecosystems is now overshooting their capacity to meet this demand by at least 50% – is misleading as it is solely due to the way anthropogenic carbon emissions are handled by the accounts; and that Footprint accounting prescribes strategies for policy makers that could be counter-productive in terms of achieving sustainability goals.

For any indicator purporting to be science-based and relevant to decision-making, criticism plays an important role in ensuring that the indicator addresses a clearly stated research question, utilizes a methodology that is appropriate and accurate in answering that question, incorporates the most recent, reliable and robust scientific findings and robust data sets as they become available, and provides information that is useful for designing policies and programs. But criticism can only serve this important purpose if it is pertinent to the indicator it is assessing.[1] In terms of Ecological Footprint accounting, one example of relevant and constructive criticism can be seen in Kitzes et al. (2009b), which identifies less robust or incomplete aspects of Ecological Footprint accounting, and then proposes various lines of research to improve the accounting methodology.

Unfortunately, the critique offered by Giampietro and Saltelli largely fails to meet this key criterion of pertinence, for they describe and then criticize a version of Ecological Footprint accounting that bears little resemblance to that provided annually by Global Footprint Network, which serves as the steward of the national level accounts, and is used by numerous government, business and scientific institutions. In particular, Giampietro and Saltelli begin their critique by claiming that the Footprint is designed to address a very different research question than the one it is actually intended to measure, then proceed to criticize the indicator for not effectively capturing their altered version of the research question. This is a bit like criticizing an accounting of greenhouse gas emissions for not effectively measuring biodiversity loss. As a consequence, the majority of Giampietro and Saltelli's criticisms simply do not apply to Footprint accounting as it is currently practiced. Other criticisms are based on older versions of the

[1] A framework for reviewing indicators is suggested in Wackernagel (2014).

http://dx.doi.org/10.1016/j.ecolind.2014.04.025
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methodology that have since been superseded, on confusions about some of the formulas utilized in calculating Footprint and biocapacity results, and on unsupported personal opinion. These criticisms are examined in more detail below.

2. What is the research question addressed by Footprint accounting?

If the objective is to assess how well any indicator methodology addresses its underlying research question, then that question must first be clearly and accurately defined. Ecological Footprint accounting is a way of assessing compliance with the first two sustainability principles identified by Daly (1990): that harvest rates should not exceed regeneration rates; and that waste emission rates should not exceed the natural assimilative capacities of the ecosystems into which the wastes are emitted. More specifically, the research question underlying Footprint accounting asks: How much biologically productive land and water area (adjusted for the productivity of this area as compared to world average),[2] is required to support the material consumption of an individual, population or activity, and how does this demand compare to the amount of bioproductive (productivity adjusted) area available? This includes demand for the production of living, renewable resources—that is, biological materials, such as food, fiber and timber, that are useful to society; for the hosting of human infrastructure, such as cities and roads; and for the absorption of anthropogenic waste, thus limiting its harmful accumulation. On the waste side, current National Footprint Accounts only include the primary driver of anthropogenic climate change, the carbon dioxide emissions that result from burning fossil fuels, land use changes, human-induced fires, and the chemical processes in cement manufacturing (Borucke et al., 2013).

To avoid double-counting, Footprint accounts only include those aspects of human demand that compete for productive area. Because Ecological Footprint accounting is based on actual rather than theoretical productivity, it takes into account the prevalent technology and land management practices of the time period that is being assessed.

The accounting tracks how much of the biosphere's regenerative capacity humans are using and compares it with how much is available. While in an ideal world the Ecological Footprint would track all demands on regenerative capacity, in the real world limits on the availability of internationally consistent and comparable datasets—a problem that is common to many indicators—limit somewhat the completeness of the accounts. Because of these constraints, while striving for maximize accuracy, when faced with choices about including or excluding unreliable data sets, the execution philosophy is conservative in that it seeks to avoid exaggeration of human demand on the Earth's regenerative capacity (Borucke et al., 2013). Although this is interpreted by Giampietro and Saltelli as an attempt to make the accounts "*media-friendly*" and "*reassuring*", it helps ensure that the results cannot be dismissed as hyperbole, and provides a minimum reference value for the magnitude of human demand on nature. Despite this conservative stance, the accounts point to significant biocapacity deficits for many economies and for humanity as a whole, a reality often ignored in mainstream economic assessments and development models.

Results for both the Ecological Footprint, the measure of demand, and biocapacity, the measure of capacity to meet that demand, are expressed in a globally comparable, standardized unit called the "global hectare" (gha). This unit represents a hectare of biologically productive land or sea area with world average bioproductivity in a given year. Since the 2011 edition of the National Footprint Accounts, Global Footprint Network also anchors this measurement unit against a reference year, typically the most recent year for which complete data is available, taking into account the varying average annual resource flow per hectare of productive land. This use of a constant global hectare is similar to the use in financial accounts of a currency value from a base reference year, such as "constant 2000 USD" as their unit of comparison. As in financial accounts, the use of constant global hectares does not average out results or hide local particularities. Instead, it provides a common unit that allows researchers to compare the Footprint of different populations and the biocapacity of specific areas across time and space (Galli et al., 2007).

Ecological Footprint accounting does not by itself measure sustainability, but offers information relevant to sustainability, namely how much biocapacity exists compared to how much people use. Knowing this information is fundamental in ensuring that the development path of societies operates within the biophysical limits of the planet. Being an accounting system, it provides a snapshot of where we are today and where we have been in the past, but it does not say where we are headed; that is, Footprint accounts are historical rather than predictive. For example, they do not address ecological and other factors that may result in an increase or decrease in biocapacity, although the accounts will reflect these changes in the years in which they are reported.

Giampietro and Saltelli's description of the research question that they suggest Ecological Footprint accounting addresses differs in two key ways from the actual research question behind Ecological Footprint accounting.

First, they argue that demand must be compared with the hypothetical productivity of ecosystems that have never been subject to human intervention, rather than with the actual productivity of the real ecosystems that exist on the planet today. They claim that this was the original intent of Footprint accounting, as expressed in the early writings of the creators of the metric. Saying "*. . .let us start again from the claims made in the 90s by the proponents of the [Ecological Footprint] analysis*," they state that there is a "*lack of congruence between the original narrative of the Ecological Footprint and the protocol presently proposed for its quantification,*" that "*the present protocol for Ecological Footprint analysis adopted by the Global Footprint Network does not match the semantics of the original narrative.*"

One could debate what the creators of the Ecological Footprint had in mind when they first proposed the analysis as well as how to interpret the semantics of a fifteen year old narrative which could arguably have been written more clearly in places. But while this may make for an intriguing historical analysis, language and sophistication evolve over time in the description of any complex indicator; this is surely as true for the Footprint as it is for any other metric that is responsive to new developments in science and the availability of more refined data sets. The intent underlying Footprint accounting has not changed since its inception. But the research question has been sharpened over the years, and the method improved. It would seem to more sense to base an understanding of the research question on how it is described in current Footprint documentation, rather than in writings from over a decade ago. The more recent literature, such as Borucke et al. (2013), makes it clear that Ecological Footprint accounting is designed to address the question of whether, in any given year, the actual capacity of productive ecosystems, which is influenced by

[2] An equivalent question would be to say: how much of the planet's regenerative biological capacity is occupied by the given human activity? This fraction can be presented as the number of average hectares out of all the hectares of biologically productive surface areas. These average hectares are called "global hectares." They are the accounting unit for both human demand on regeneration, as well for adding up the availability of productive area.

technological interventions and management practices, is keeping up with human demand on these ecosystems.

The research question addressed by Ecological Footprint accounting avoids the need for hypothetical speculation about what an ecosystem might produce in the absence of any human intervention, and it does not require drawing an arbitrary boundary between land areas that are in their "natural" state and those that have been managed and modified. By providing measures that are directly observable and measurable, the results become more robust and are subject to empirical verification.

Second, Giampietro and Saltelli's version of the research question, in addition to tracking biocapacity, includes an evaluation of factors that contribute to the resiliency or fragility of biocapacity, and would thereby necessitate the creation of a hybrid indicator that would reflects not only human pressure, but also impact on productive ecosystems. This distortion of the actual research question behind Ecological Footprint accounting is evident in their complaint that in the Global Footprint Network protocol, "*the accounting only provides information on different levels of alteration of ecosystems, comparing the local system with the global average*." But Ecological Footprint accounting does not measure alterations of ecosystems. Instead it documents current demand and compares it with current supply. It is true that demand and supply could be documented more fully, a limitation well-acknowledged in the published Footprint literature (Galli et al., 2012a; Kitzes et al., 2009a,b; Wackernagel et al., 2014). Tracking impacts on ecosystem productivity is certainly relevant for sustainability assessments, but Ecological Footprint accounts are not designed to measure this aspect. Other indicators can be used in conjunction with Ecological Footprint and biocapacity data to provide a more comprehensive description of both the magnitude of human demand and impact on ecosystems.

As Giampietro and Saltelli correctly note, in assessing the sustainability of society's current resource metabolism, it is critically important to understand the way various stresses may negatively impact biocapacity. The same point is made in a recent publication by Wackernagel et al. (2014): "Within the domain of Ecological Footprint research, 'fragility of biocapacity' has not been researched in detail. Such research would provide deeper insight into how much of the currently measured biocapacity may not last, for instance due to water, energy or soil constraints." But this is not the same as simply aggregating measures of impact variables, along with measures of the Footprint and biocapacity, into a single index which would then be largely uninterpretable. Attempts to construct these kinds of composite indices typically rely on expert opinions or otherwise subjective weightings of the contributions of each the included variables, making the final result relatively arbitrary. Such approaches generally lack a clear research question (i.e. a testable hypothesis phrased as a specific query). Accounting systems driven by clear research questions can effectively aggregate different aspects of an issue, provided these can be captured using a common measurement unit. Aspects that cannot be captured in the same unit need to instead be presented in parallel if the results are to be meaningful.

3. Is the Ecological Footprint overly aggregate?

Despite criticizing Ecological Footprint accounting for not incorporating stress measures into the accounting, and thus not providing a sufficiently nuanced and complete sustainability assessment, Giampietro and Saltelli also criticize Footprint accounting for supposedly attempting to capture too complete a picture of sustainability: "*The [Ecological Footprint] approach cannot handle the complexity of sustainability because of its goal to deliver a simple narrative (a single number addressing all dimensions of sustainability)*." They are quite correct in pointing out that Footprint accounting cannot, on its own, "*handle the complexity of sustainability*," for it was never intended to do so. The Ecological Footprint is not a complete measure of sustainability (Galli et al., 2012a), but instead offers information relevant to one critical aspect of sustainability – a minimum but not sufficient condition (Bastianoni et al., 2013) – that the rate at which the human economy demands renewable resources, whether for consumption or carbon sequestration, remains within the planet's capacity to generate these resources. Giampietro and Saltelli's conclusion is again is based on a distortion of the research question. It is not the intent of Footprint accounting to offer "*a single number addressing all dimensions of sustainability*;" instead it provides data that focuses on only on a single, albeit important dimension: demand on regenerative capacity.

Footprint accounts are aggregate in the sense that they bring together a variety of demands that compete for regenerative capacity—for provision of the food, fiber and timber resources consumed by society, for hosting infrastructure, and for sequestering carbon emissions. The Footprint accounts also bring together the various types of ecosystem that supply most of the regenerative capacity used by humanity—cropland, grazing land, forest, and fishing area. To avoid double counting, the accounts include only those demands that compete for regenerative capacity—that is, that require non-overlapping bioproductive areas. Given constraints on data availability, current Ecological Footprint accounts do not completely capture all competing demands on biocapacity, and it is likely that they never will be able to do so. One can then ask, despite these limitations, whether Footprint accounting is effective in capturing even this single dimension of demand on regenerative capacity. If it does not, then – like any metric that does not effectively measure that which it purports to measure – further discussion of the value of the metric is moot. Giampietro and Saltelli offer a number of criticisms that suggest Footprint accounting fails to meet this value criterion; these criticisms are reviewed below.

4. Is measuring actual or estimating "natural" biocapacity more useful?

Giampietro and Saltelli criticize the way the Footprint accounts measure biocapacity. Their primary complaint, repeated in a variety of different criticisms, is that the accounts reflect the current, actual productivity of ecosystems rather than the productivity that would have existed in some ideal state wherein these ecosystems had never been subject to any human intervention. This complaint appears to be more of a philosophical difference about what they believe *should* be measured, rather than a comment on how the accounts *actually* calculate biocapacity. For instance, they say that "*the biocapacity assessed under prevailing technology and resource management of a given specific year does not coincide with the biocapacity that would be provided by natural processes alone*." While it is not completely clear how "*natural processes alone*" could be measured, it is absolutely true that biocapacity results in the Footprint accounts are meant to reflect prevailing technology and resource management, as this is in full alignment with the underlying research question. Measuring Footprints based on actual rather than an estimate of ideal productivity was a choice made in order to avoid introducing speculative elements such as the definition of a "natural state" into the metric.

Giampietro and Saltelli's proposal that biocapacity should be assessed in terms of hypothetical rather than actual productivity is made quite explicit in their argument that "*if the idea is to confront the actual demand for natural resources and ecological services of a given economy or system (local assessment of the altered system) against what would be a sustainable supply in relation to the biosphere's regenerative capacity (when living on the interest of the* *natural capital...), then we should use two independent data sets: (1) An assessment of the economy of the system under analysis (the altered situation), i.e. measuring the actual demand that may or may not be met by altering in a non-sustainable way the natural capital through stock depletion and filling of sinks; and (2) An independent assessment of what would be the natural regenerative capacity of the natural capital of the system under analysis ("nature's supply of biocapacity") assuming a natural, unaltered state (the natural capital of a hypothetical reference state of undisturbed ecological processes). This second assessment is necessarily based on a hypothetical situation...*" Giampietro and Saltelli are clearly stating here that in their preferred version of Ecological Footprint accounting "*actual demand*" should be compared with "*a hypothetical situation*", being the "*natural regenerative capacity of the natural capital of the system under analysis*" which assumes "*a natural, unaltered state*" defined as "*the natural capital of a hypothetical reference state of undisturbed ecological processes*."

What this means, one might assume, is that they are arguing that current demand should be compared with the productivity of ecosystems as they might have existed had humans never existed on the planet, or at least as they were before humans began applying technology or management practices to these productive areas. Although this type of comparison would provide interesting information, one wonders how the productivity of these natural ecosystems might actually be determined, given that it is questionable as to whether any undisturbed areas of productive land or water exist on the planet today. Given the conceptual and practical challenges of assessing "unaltered states," measuring actual productivity would seem to provide a more robust and useful starting point. Doing so does not, of course, denigrate the usefulness of complementing Footprint and biocapacity measurements with assessments that evaluate to the extent to which biocapacity may be reduced or enhanced over time.

In addition, one wonders how "unaltered" is to be defined, as obviously cropland would not exist at all absent human intervention. Is clearing rocks from soil by hand in order to plant crops somehow more "natural" and less technological than moving them using an animal or a machine? Is organic agriculture less dependent on management practices because it utilizes crop rotation rather than the application of manufactured fertilizers? While an understanding of ideal versus actual productivity may be useful, for example, in work on restoration of ecological services or biodiversity, it is not at all clear that most policymakers would find a comparison of current consumption with the hypothetical productivity that may have existed in some ideal pre-agrarian world more useful for resource management purposes than a comparison of consumption with the actual productivity of ecosystems as they exist today.

5. Are global hectares a measure of actual or hypothetical productive area?

Giampietro and Saltelli criticize global hectares, the units in which the Ecological Footprint and biocapacity are measured, as representing hypothetical rather than actual productive area. For instance, in commenting on the ability of Ecological Footprint accounting to track the biocapacity in an individual country, they say, "*What is measured in the [National Footprint Accounting] protocol are densities of virtual flows produced by generic virtual global hectares and determined by 'yield factors' and 'equivalence factors.*'" This comment is puzzling, as global hectares are simply a way of converting hectares of a given nation and land type into a common unit that allows comparison of productivity across different countries (the purpose of the yield factor) and land types (the purpose of the equivalence factor) using a unit that represents the average productivity per hectare of all these included areas (Galli et al., 2007). It is based on actual, measured flows, not virtual flows. For the base reference year, a global hectare represents a percentage of the globe's total biocapacity in that year (one divided by the total number of biologically productive hectares on the planet in that year, times 100%. As a consequence, the number of global hectares is equal to the number of biologically productive hectares on the planet in that reference year). As explained earlier, to aid comparison of productivity and demand across different years, "constant global hectares" are calculated by adjusting the value of global hectares as measured in any given year using the productivity data of a selected reference year (see also Borucke et al., 2013).

Yield factors, which adjust for national differences in the productivity of each individual type of productive area, and equivalence factors, which adjust for the productivity differences across different types of productive area, are used in the calculation of global hectares (Borucke et al., 2013). These factors are recalculated in the National Footprint Accounts for every year and every country. The calculations are transparent and well-documented (Galli et al., 2007; Borucke et al., 2013; Ewing et al., 2010; Kitzes et al., 2008).[3]

If one preferred, for example, to express the biocapacity of any particular nation in Dutch average hectares, that could easily be done by comparing the average yields in that nation with the average yields in the Netherlands. While reporting data in Dutch average hectares might be useful to inform resource management practices in the Netherlands, for the purpose of international comparisons, this would seem less convenient than using global hectares (Galli et al., 2007).

Conversion of national average hectares into global hectares is similar, to using U.S. dollars as a common denomination in financial analysis across countries with differing currencies. Just as the cost of a house in Switzerland, sold in Swiss francs, does not become hypothetical if one chooses to express that cost in dollars, Dutch biocapacity does not become hypothetical if one chooses to express it in global hectares rather than Dutch hectares. A similar parallel can be drawn to the use of "CO_2 equivalents" in expressing the global warming potential of emissions other than carbon dioxide. Converting a quantity of methane emissions into its CO_2 equivalent does not make the rise in temperature it is responsible for any less real, and the use of this common unit allows the combined warming potential of different greenhouse gases to be calculated.

6. Is the carbon component of the Ecological Footprint misleading?

The carbon component of the Ecological Footprint is a measure of the regenerative capacity required to sequester the fraction of anthropogenic carbon dioxide emissions that is not absorbed by the oceans. In other words, it represents the regulatory ecosystem services necessary to avoid increasing the carbon accumulation in the atmosphere and to help prevent disruption of the global climate. In doing so it is based on the same assumption used by the United Nations Reducing Emissions from Deforestation and forest Degradation (REDD) Program and other carbon credit programs, that the incorporation of carbon dioxide into the biomass of growing trees which are not destined for harvest can offset its undesirable accumulation in the atmosphere. This linkage also plays a well-established role in the findings reported by the Intergovernmental Panel on Climate Change (IPCC). Carbon emissions are included in Ecological Footprint accounting because sequestration of these

[3] The calculation templates are available at no charge to academic users under a National Footprint Accounts Learning License (see http://www.footprintnetwork.org/en/index.php/GFN/page/methodology/).

emissions by forests competes for use of this same productive area for harvesting of wood and wood products; simply put, a tree can either be left standing to continue absorbing carbon or it can be cut down for wood, but not both at once.

Because some analyses may require excluding the carbon or other components of the Footprint, they are reported separately in addition to in aggregate. For instance, Weinzettel et al. (2013) used just the non-carbon Footprint components to assess how increasing affluence might be driving global displacement of land appropriation. Similarly, Galli et al. (2013) focused on just the cropland and forest components in their analysis of Swiss consumption trends and their implications for ecosystems and biodiversity outside of Switzerland.

In a number of their criticisms, Giampietro and Saltelli appear to equate carbon emissions with energy use, and imply that the carbon Footprint[4] is intended to track the latter. They use the terms "energy" and "fossil fuel" interchangeably, which is confusing and can be misleading. For example, they say that "*The assessment of the Ecological Footprint of consumption can be divided into two main components: 'non-energy-related biocapacity'* and '*energy-related biocapacity*'."[5] And again, they state that "*It is impossible to represent the energetic metabolic pattern of a modern society using only a single numeraire for accounting energy*." But Ecological Footprint accounting does not directly track energy use by society; instead it accounts for carbon emissions, because it is demand for sequestration of these emissions, rather than energy use per se, which competes with other demands on biocapacity. One can however, use Footprint accounts to evaluate the biocapacity implications of various energy options or to explore energy scenarios. One such scenario, for example, was included in the Footprint projections developed for the World Business Council for Sustainable Development's *Vision 2050* project (WBCSD, 2010).

Giampietro and Saltelli claim that "*when calculating the carbon footprint the [Ecological Footprint] protocol first has to translate the given flow of energy carriers consumed in a country into a given flow of CO_2 emission* [*sic*]." This is only partially correct: while energy usage may be translated into CO_2 emissions in certain sub-national Footprint analyses where direct data on emissions is not available (for example, in calculating the carbon component of the Footprint for a product or a municipality), at the national level Ecological Footprint accounting does not need to do this translation, instead relying directly[6] on emissions data from the International Energy Agency (IEA 2012). In addition, the carbon Footprint includes more than just emissions from the combustion of fossil fuels; at the global scale (and likely soon at the national level), it also accounts for emissions from the lime calcination chemical reaction in cement production, from human induced fires and from land use change. Perhaps, as Giampietro and Saltelli suggest, this emissions data is "*problematic*"; if so, this is a problem not only for Footprint accounting, but also for the REDD program, the IPCC, and any others who rely on the accuracy of this data.

One further clarification: Giampietro and Saltelli state that a portion of the CO_2 emissions accounted for by the carbon Footprint "*may derive from the virtual tons of oil equivalent of electricity generated by nuclear power*." While this was true in earlier versions of Footprint accounting, it has not been the case since 2008, when the methodology was revised in accordance with the recommendations of Global Footprint Network's National Accounts Review Committee.[7]

Giampietro and Saltelli also criticize the carbon Footprint for not including the biocapacity required to "*to get and use energy inputs*", that the Ecological Footprint "*assessment ignores the space required for producing the energy input consumed by society*." By "*producing*," they are presumably not referring to the exploration, extraction, refining and transportation of fossil fuels, as the biocapacity required to carry out these activities is included in the Footprint accounts. Instead, similar to the approach used in energy accounting (Odum, 1988), they seem to be referring to the bioproductive capacity incorporated over geological time periods in the creation of fossil fuels, or perhaps the biocapacity that would be required to provide energy if renewable biomass were to be substituted for all the fossil fuel being used today. This criticism again arises from a philosophical difference regarding Giampietro and Saltelli's preference as to what they believe the Footprint *should* be measuring versus what it is actually designed to measure. They argue that, in accounting for fossil fuel use, the current Footprint "*protocol has dropped the assessment of the supply side altogether*," and that this is somehow inappropriate.

It is true that in the formative discussions of the Footprint methodology, the land required for the original generation of fossil fuel was considered but then rejected as an alternative way of calculating the carbon component (Wackernagel and Rees, 1996). But as the logic of Ecological Footprint accounting evolved and sharpened, it was recognized that if the research question is about comparing current annual demand on ecosystems with their current annual capacity to meet this demand, the land area required to generate fossil fuels is not relevant, as this occurred long ago over geological epochs of time, and does not constitute a current demand on biocapacity in human-scale time. In fact, from a Footprint perspective, it makes no difference if the fossil fuels currently being extracted from the lithosphere are of biological or, as was earlier believed, geological origin. The sequestration of carbon dioxide emissions, however, does constitutes a demand on ecosystems that is relevant in human time scales, as reflected in the rapidly growing accumulation of carbon in the atmosphere and the resultant climatic changes that have already become apparent.

Giampietro and Saltelli also allege that "*the supply of fossil energy (a nonrenewable resource) is assumed to be unlimited in the future by default.*" As explained above, this is not assumed in Ecological Footprint accounting, which does not address the supply of fossil fuel at all, only the emissions produced when it is burned, since it is the need for sequestration capacity for these emissions that competes for productive area with other demands on biocapacity. In planning for long-term sustainability, constraints on the availability of biocapacity for carbon sequestration are likely to be a far more limiting factor than the depletion of fossil fuel stocks found in the lithosphere (Meinshausen et al., 2009; Carbon Tracker, 2012).

7. Units mismatch: does the carbon Footprint compare flows with stocks, or flows with flows?

Giampietro and Saltelli maintain that the Footprint "*approach establishes a quantitative equivalence between a flow measured in tons of CO_2 per year – corresponding to the official SI dimension of kg/s – and a finite stock size expressed in biomass per hectare of land*

[4] For the sake of simplicity, the carbon component of the Ecological Footprint, measured in global hectares, will herein be referred to as the carbon Footprint. This should not be confused with the different, widespread use of the latter term to refer simply to the tons of carbon dioxide emissions associated with a human activity (see Galli et al., 2012a for further details on this distinction).

[5] We assume, for example, that here they mean 'fossil fuel-related' and 'non-fossil fuel-related' Footprint.

[6] The carbon embedded in traded products is not disaggregated in the data available from IEA, and instead is estimated using embodied energy coefficients. This introduces a degree of uncertainty in the allocation of national carbon Footprints, but not the total global carbon Footprint.

[7] See http://www.footprintnetwork.org/en/index.php/GFN/page/national_accounts_review_committee/ for additional information about the National Accounts Review Committee.

Please cite this article in press as: Goldfinger, S., et al., Footprint facts and fallacies: A response to Giampietro and Saltelli (2014) "Footprints to Nowhere". Ecol. Indicat. (2014), http://dx.doi.org/10.1016/j.ecolind.2014.04.025

capable of fixing a certain amount of carbon – corresponding to the official SI dimension of kg/m². *This procedure violates the elementary logic of accounting, as well as the formal matching of dimensions in the resulting quantitative expression, i.e. the [Ecological Footprint] uses an identity in which the terms on the right and left of the equal sign are measured in different units*." This claim is incorrect: within Footprint accounts, flows are compared to flows. However, these flows are measured in global hectares, areas with world-average flows that correspond to a specific rate of resource regeneration. On the demand side, the carbon Footprint is based on the number of tons of carbon dioxide that are being emitted through anthropogenic activities (minus the tons absorbed by the oceans) per unit time, typically in a given year ($t\ CO_2\ yr^{-1}$). This flow is then converted into the overall area (global hectares) needed to sequester it by dividing it by the area required to take up this many tons of carbon dioxide in that year:

$$EF_{\text{carbon}} = \frac{\text{annual amount emitted}}{\text{sequestration rate per area}} = \frac{CO_2[t]/\text{yr}}{CO_2[t]/\text{yr} * \text{area [gha]}} = \text{area [gha]}$$

On the biocapacity side, the available area of forest with average sequestration rate – expressed in tons of carbon dioxide sequestered per hectare of land per unit time – is also measured and expressed in global hectares:

$$\text{biocapacity [gha]} = \text{relative productivity [gha/ha]} \times \text{area [ha]} = \frac{(\text{annual amount regenerated in this ha [t/ha]})}{(\text{regeneration rate of a world average ha [t/gha]})} \times \text{area [ha]}$$

Therefore:

$$\text{biocapacity}_{\text{sequestration}} = \frac{(\text{annual amount sequestered by this ha [t/ha]})}{(\text{sequestration rate of a world average ha[t/gha]})} \times \text{area [ha]} = \text{area [gha]}$$

Even though all ecosystems, to a greater or lesser extent, can sequester CO_2, the Footprint accounts compare the carbon Footprint with forests' ability to sequester – in other words with their biocapacity for sequestration. In other words, sequestration rates per global hectare are calculated from average forest sequestration capacity. This is in part because reliable global data is not available on carbon sequestration other than in forest—for example, in soils, because forests likely provide the majority of terrestrial ecosystems' sequestration of carbon, and because the is the approach adopted by the UN Framework Convention on Climate Change, the UN Forum on Forests, the IPCC, and other major international bodies. Note that in Footprint accounting, forests provide two different ecological services, carbon sequestration and provision of forest resources products (timber, fibers and pulp, fuelwood), which compete for the capacity of forests to generate tree biomass.

8. Does Ecological Footprint accounting assume perpetual forest? Is it based on virtual forest area?

Giampietro and Saltelli assert that "*A hectare of forest cannot grow (and fix CO_2) forever*", and then quote Haberl et al., 2001 (2001, p.30) claim that "... *only young forests fix significant amounts of carbon*."[8] Ecological Footprint accounting is based on actual forest sequestration rates in any given year as reported by FAO (2010) rather than on guesses about how sequestration rates might change in the future. In other words, as with all other Ecological Footprint components, the carbon Footprint is based on current productivity, in this case the world's current forest sequestration capacity. The calculations reflect the net amount of carbon dioxide current forests (primary, other naturally regenerated and plantations, following the UN FAO classification) can sequester per year, in accordance with IPCC published data sets. If the average sequestration capacity of forests were to diminish, whether because of forest maturation or lower net forest productivity due to climate change or other factors, the Footprint accounts would reflect this as a larger Footprint per ton of carbon dioxide emissions. In other words, nature would have even less capacity to sequester anthropogenic carbon emissions.

The value of the carbon component of the Ecological Footprint is calculated using the measured global average carbon sequestration rate of forest, and thus indicates the amount of actual forest area needed to sequester a given annual carbon emissions flow. It does not indicate, as Giampietro and Saltelli suggest, the use of "*virtual*" forests. Nevertheless, because individual forests do not necessarily sequester at the average rate, a global hectare of forest can represent an area of forest larger or smaller than a physical hectare. In addition, while it is possible for the carbon Footprint to exceed the forest biocapacity available for sequestration (that is, forest not otherwise being harvested for wood), this does not mean that the carbon Footprint is based on virtual forest, but simply that there is not sufficient real forest available to sequester all anthropogenic carbon emissions.

9. Will the Ecological Footprint of carbon change as technological solutions to the storage of CO_2 develop?

Giampietro and Saltelli state that "*the [Ecological Footprint] protocol proposes a demand of land equivalent to absorb the CO_2 emissions. However, other possible options exist for dealing with excess CO_2, such as storage below ground or under sea or biochar. Clearly, each one of these options (or combinations thereof) may result in an entirely different estimate of land requirement and, consequently, in different assessments of the Ecological Footprint of the carbon footprint* (Van den Bergh and Verbruggen, 1999)."[9]

In this, Giampietro and Saltelli are correct, but it is not a weakness in the Footprint Accounts; instead, it means the accounts are operating as intended in tracking the biocapacity required to sequester carbon dioxide emissions if these are not to accumulate in the atmosphere. If biochar, ocean deposition, carbon capture and storage (CCS) or any other technology is deployed that successfully reduces anthropogenic carbon emissions, less sequestration capacity would then be required to absorb the remaining emissions, and the carbon Footprint would decline accordingly. However, Giampietro and Saltelli's argument that "*the rigid definition of 'prevailing technology' does not allow the Ecological Footprint to compare among themselves possible new technical solutions (e.g. geo-engineering for CO_2 capture and storage or developing effective CO_2 reservoirs under the sea*)" is not correct; while Footprint accounts are historical, and reflect the impact of prevailing technology on carbon emissions, scenarios can easily be developed to assess the carbon Footprint implications of deploying new technological options for reducing carbon emissions.

[8] Recent evidence (Luyssaert et al., 2008; Stephenson et al., 2014) suggests that this assumption may not be correct.

[9] See also van den Bergh and Grazi's (2013) paper repeating a similar argument, or Blomqvist et al. (2013).

10. Should carbon and non-carbon Ecological Footprint components be aggregated? Is overshoot solely due to carbon?

Demand for food, fiber and timber resources and demand for carbon sequestration directly compete for the mutually exclusive use of bioproductive areas, which is why both types of demand on the Earth's regenerative capacity are included in the Footprint accounting system. Furthermore, because there is some degree of substitutability among these different demands, tradeoffs among them are often made more transparent when they can be aggregated within a single accounting framework and expressed in the same units. For example, over the past half-century, human population has been growing at an unprecedented rate, and with it, the demand for food. As Giampietro and Saltelli correctly point out in their Figure 1 (adapted from Ewing et al., 2010), at the global level the carbon Footprint increased rapidly over this period, while the sum of non-carbon components has increased little if at all.[10]

This is consistent with the observation that the rapid growth of agricultural productivity has been enabled largely by fossil fuel-based inputs (Lotze-Campen et al., 2010; Tilman, 1999; Woods et al., 2010). Without these higher yields, far larger area demands would be needed to supply humanity's increased consumption of agricultural products. In addition to these agricultural inputs, other uses of fossil fuels—tracked by Footprint accounts only in terms of the associated CO_2 emissions—have driven growth in the carbon Footprint while dampening growth of the non-carbon Footprint components. For example, the substitution of fossil fuel-based synthetic fibers for natural fibers in clothing, the extensive use of plastics instead of wood and paper for wrapping and other forms of containment, the replacement of timber used for heating purposes with oil, natural gas and electricity, and the increasing reliance on synthetic building materials that supplement or supplant the use of cotton, wool, timber and pulp have contributed to the growth of the carbon Footprint while slowing the growth on the non-carbon components. This is not to suggest that these tradeoffs had no consequences beyond those captured by Footprint accounting. Intensification of agricultural yields through fossil fuel inputs and the increasing use of synthetic materials have been associated with a wide variety of significant environmental impacts such as soil loss, toxic pollution, and a decline in biodiversity (Butchart et al., 2010), which are not directly tracked by the Ecological Footprint (Galli et al., 2013; Kitzes et al., 2009a).

Moreover, while the carbon Footprint component constitutes approximately 50% of humanity's total Footprint, Galli et al. (2012b) have shown this percentage varies noticeably between low-income (25% of total Footprint), middle-income (46%) and high-income (65%) countries. In low-income countries, cropland is the largest Footprint component, comprising approximately 45% of total Footprint.

Because of this tightly woven pattern of interrelationships among all the Footprint components, overshoot cannot meaningfully be attributed to any single component, but instead reflects the sum of all demands. If fossil fuels had not been used over the past century to increase agricultural yields and to provide substitutes for many renewable resources, it is likely that the non-carbon components of Footprint would have displayed considerable growth over this period. And even at current rates of carbon emissions, without these other competing demands on biocapacity, humanity's global Footprint would not be overshooting global biocapacity.

Should the built-up component be excluded from the Ecological Footprint? Giampietro and Saltelli "*wonder why [the built-up] land use category (representing a negligible fraction of total land) is included in the protocol in the first place*." The reason is simple: Because siting infrastructure on productive land competes with other uses of that land for the generation of resources, and thus must be accounted for. Built-up land is treated as equivalent to cropland because cities were historically built on fertile land – typically not just on average cropland but on the best cropland, as documented for the US (Imhoff et al., 1997, 2000). Even though the Footprint and biocapacity of built-up area are always equal in terms of global hectares and thus this component does not contribute to overshoot, accounting for built-up land shows how much of total biocapacity is being utilized for this service.

11. Do Ecological Footprint results reflect directly measureable properties of the world?

Giampietro and Saltelli present the following case. "*The accounting protocol of the Ecological Footprint generates numbers, both in the assessment of the demand for and supply of biocapacity, that do not refer to any directly measurable (observable) attribute defined on any given descriptive domain (see Giampietro et al., 2006). Indeed, numbers are obtained by mixing:*

(1) Characteristics of systems observed at different scales. For instance, in the definition of the virtual area equivalent (global hectares) of the demand, local consumption (measured at the local scale) is divided by world average yields (measured at the global scale). When defining the virtual area equivalent of the supply of biocapacity, local hectares (measured at the local scale) are multiplied by yield factors derived from global yields;

(2) Virtual characteristics derived from quantitative variables belonging to different descriptive domains. For example, hectares of marine resources required to produce salmon are transformed in virtual hectares of grazing land required to produce beef and are summed to virtual hectares of forever-growing forest taking up the virtual tons of CO_2 emission (some of which may derive from the virtual tons of oil equivalent of electricity generated by nuclear power. . .)."

The use of a global hectare in Footprint accounting does not suffer from a problem of using different, unobservable scales; it is simply a way of expressing productive capacity in a common unit – a hectare that grows renewable resources at a world average rate. It is no more virtual than photosynthesis is virtual. Expressing the productivity of different types of ecosystems or areas in different locations in a common unit is similar to the use of a common currency, such as constant US$, to conveniently compare the output of different industries or counties. It is also similar to the emergy approach (Odum, 1988), which measures the solar energy needed through time to produce the natural and artificial resources that support human activities on a given area. In emergy analysis, the contribution of each considered input (natural and artificial resources) is converted into a common unit of measure, the solar energy joule (Sej) through conversion factors (i.e. transformity or specific emergy) called Unit Emergy Values (UEV) (Odum, 1988). To build on the parallel between emergy and Ecological Footprint, the combined use of yield and equivalence factors in Footprint accounting serves the same function of the UEVs in emergy accounting.

Production of pianos and shoelaces, although very different categories of consumables, can both be described in tons, dollars or

[10] Giampietro and Saltelli used an older graph in Fig. 1, which did not yet use constant global hectares. With the introduction in 2012 of constant global hectares, current graphs of changes over time in the cropland Footprint and biocapacity now track enhanced productivity as an increase in the number of constant global hectares.

Please cite this article in press as: Goldfinger, S., et al., Footprint facts and fallacies: A response to Giampietro and Saltelli (2014) "Footprints to Nowhere". Ecol. Indicat. (2014), http://dx.doi.org/10.1016/j.ecolind.2014.04.025

any other unit measuring a common dimension that these categories of objects share. Similarly, production which depends on the Earth's ability to regenerate resources via photosynthesis by using energy from the sun and other inputs can be described using a common unit that reflects the amount of regenerative capacity required (Rees, 2013). And whether that capacity is obtained from a large area of low-productivity land or a smaller area of high productivity land, the capacity required to grow say, a cubic meter of timber, is the same, regardless of where on the planet this capacity is obtained.

12. Is the Ecological Footprint useful for policymakers, or is its use counterproductive?

Giampietro and Saltelli raise a number of concerns to suggest that Ecological Footprint accounting is not useful for policymakers. Each of these concerns is addressed in turn below.

1. **Is Ecological Footprint accounting incomplete?**
   Ecological Footprint accounts leave out many aspects of sustainability by design, as explained above. It only focuses on a single research question reflecting a single dimension of the sustainability issue —demand on regenerative capacity— and not on sustainability as a whole. Even so, in addressing just this one question, current Ecological Footprint accounts do not completely capture all competing demands on biocapacity, nor is it likely they will they be ever able to. Nevertheless, it provides reasonably complete tracking of two key aspects of societal metabolism—consumption of renewable resources, and climate-altering carbon emissions–and in comparing them with the Earth's capacity to meet these metabolic demands, provides an important indication as to whether society will be able to continue on its present course unobstructed or will encounter limits.
2. **Is Ecological Footprint accounting prescriptive?**
   The Ecological Footprint is set up to measure one biophysical dimension of human interaction with the environment. As any science-based metric built on a research question, it describes what exists and then leaves it up to the user to decide how to use this information, and what values to apply to it. Like any measure, it can also be subject to misinterpretation. Footprint accounts do not tell you if a Footprint is too big or too small, or if it is fair that the per capita Footprint of one country is larger than that of another. Similarly, a measure of weight is a description: whether something is too heavy or too light is an interpretation, which depends on the context, on other variables and on value systems. Metrics enable judgments, sometimes contradictory ones, but in and of themselves are not judgments. But if a metric is relevant, it can serve as the evidence base for making interpretations or offering prescriptions.
3. **Is it problematic that "the protocol is continuously being adapted in response to criticism"?**
   Global Footprint Network, which serves as the global steward of the National Footprint Accounts, is committed to continuous improvement of the accounting method in order to more accurately answer the research question it addresses. Granted, too frequent methodological changes could potentially make it more difficult for users to apply and interpret the Footprint results, and for this reason stakeholders interested in monitoring nations' Ecological Footprints through time and/or setting Footprint reduction targets are advised to always look at the time trends from the most recent edition of the Accounts. Seeking a balance between stability and methodological improvement is challenge common to all science-based indicators, which to remain valid need to incorporate, rather than ignore, better data and new scientific knowledge as they become available. It is not clear why Giampietro and Saltelli feel this is undesirable.
4. **The Ecological Footprint is media friendly**
   In one of their more perplexing criticisms, Giampietro and Saltelli suggest that the Ecological Footprint is problematic because it is "*media friendly*". Conversely, it seems desirable for a science-based indicator to be easily understood and to readily communicate its relevance. As a result of its being reported in the media, Ecological Footprint research has generated science-based discussion about ecological limits among both the general public as well as those who have the greatest leverage in societal decision making, as acknowledged even by critical external reviewers (Wiedmann and Barrett, 2010).
5. **Are Ecological Footprint accounting results overly "*reassuring,*" and thus generate complacency?**
   Giampietro and Saltelli suggest that Ecological Footprint accounts underplay the urgency about "*man's pressure on the planet and its ecosystems*," that their "*mild verdict found ready approval with the political establishment*," and that the results depict "*a much rosier state of affairs than an ecological analysis would warrant.*" This claim is difficult to evaluate, as Giampietro and Saltelli fail to provide any evidence that policy makers or others have chosen to remain passive on environmental challenges after being convinced by Footprint data that there is no longer any need for concern. When Switzerland or Italy learns they are using four times the biocapacity they have, is this taken as reassuring? Is 50% global overshoot perceived as a rosy state of affairs, particularly when considering that biodiversity preservation likely necessitates that humans use less than the entire biocapacity of the planet and studies affirm that decision makers have failed to meet the 2010 biodiversity targets set by the Convention on Biological Diversity (see Butchart et al., 2010)? Knowing that if everyone on the Earth consumed like an average American keeping up with the demand would require more than four planets, the fact that a large and growing Chinese middle class is seeking to emulate this lifestyle (Galli et al., 2012b) would seems more likely to engender concern rather than complacency.
6. **Does the Ecological Footprint accounting prescribe perverse, counter-productive policy solutions?**
   Giampietro and Saltelli state that "*in spite of the name —biocapacity—this indicator depends essentially on the relative amount of synthetic fertilizers, tractors and pesticides used per hectare in the local system and at the global level. This logical inconsistency has been flagged earlier by Lenzen et al. (2007, p. 7): 'Several national governments in Europe include increasing the proportion of the national area of farmland under organic agricultural practices in their strategies for sustainable development. But the immediate effect on national accounts of the choice to convert from conventional to organic agriculture will decrease biocapacity, due to the short term reduction in yields from these areas.*'"
   Biocapacity, as explained earlier, reflects not the hypothetical ability of an ecosystem to produce resources, but instead, the actual productivity. As such, biocapacity may vary over time with the application of technologies, such as the use of fertilizers, and with management practices. Some of these technologies and management practices may be beneficial in the short-term, but detrimental in the longer term. Footprint accounts do not capture any of these detriments or benefits other than to the extent they may impact current Footprint components or affect future productivity. For example, the application of fertilizers to cropland and the use of mechanized tilling, planting and harvesting may, at least for time, increase yields and thus measured cropland biocapacity, but at the same time the practices will likely increase the magnitude of a country's carbon Footprint. In addition, there may be other detrimental impacts of these practices,

such as topsoil loss or a decline in microbial biodiversity, which are not captured in the Footprint accounts. For this reason, other variables must be considered before deciding whether increasing or decreasing the Footprint or biocapacity is a good idea; the accounts on their own do not tell you this. It may sometimes be preferable to choose a higher Footprint option if doing so has other benefits, such as lessening pollution and biodiversity pressure in the substitution of organic for conventional industrial agriculture. But the fact that there are additional considerations for sustainability does not mean there is a problem with the way biocapacity is defined or calculated, for as Lenzen points out, a shift to organic agriculture may, at least initially, mean that the same area of farmland will be able to meet a smaller food demand. It should not just be assumed that organic agriculture will necessarily have a smaller Footprint, just as it should not be assumed that products obtained from local growers will have a smaller Footprint than those shipped from overseas. Both are empirical questions that depend on the particular details of each situation.

Different agricultural production strategies have been compared using Footprint accounts. Wada (2003), for example, showed that tomatoes grown in greenhouses in British Columbia have ten to twenty times larger Footprints than tomatoes grown outdoors and in season in the same area. Ecological Footprint accounting does not judge which option is preferable; it simply sheds light on the resource flows associated with each one. While staying within nature's biocapacity budget is a necessary condition for sustainability, it is not the only one.

Giampietro and Saltelli (and others, e.g. Lenzen et al., 2007) also claim that Ecological Footprint accounts are biased in favor land-conversions from forest to cropland, and that this can distort policy decisions. They argue that "*standing forests are weighted by an equivalence factor of 1.4, but once cleared and turned into plantations of palm oil, they are registered as primary crop land, the equivalence factor of which is 2.2... The conversion of biodiversity-rich tropical forests to monocultures of palm oil thus results in a misleading increase in biocapacity, even though the robustness and long-term regenerative capacity of ecosystems are compromised.*" But this incorrectly compares areas only through their equivalence factor, and disregards the role of yield factors. Converting a hectare of equatorial forest into cropland will not necessarily result in the biocapacity increase that Giampietro and Saltelli describe. As forest, this hectare of land in the equatorial zone is likely to have biomass productivity higher than world average forest and thus a yield factor greater than one (see Borucke et al., 2013 for additional info on how these factors are calculated). However, most of the nutrients in tropical forests accumulate in the trees rather than in the soil. Thus once this hectare is converted to cropland, its crop productivity is soon likely to drop below the world average for cropland, and thus would have a yield factor lower than one. The higher equivalence factor for cropland could therefore potentially be more than compensated for by the lower yield factor, resulting in an overall decrease in the biocapacity associated with each hectare converted from forest to cropland.

7. Does Ecological Footprint accounting provide useful information about trade? Is it biased toward or against trade?

Questioning the Footprint's policy relevance, Giampietro and Saltelli ask, "*Can the [Ecological Footprint] analysis shed light on the advantages and disadvantages of trade for the countries involved? Does it provide any information on whether the imported agricultural commodities damage the local agro-ecosystems in which they are being produced?*"

These are two very different questions. The answer to the first is yes, there is great value in understanding the extent to which a country is dependent on the capacity of a trading partner to continue providing the resources that the former imports, and great risk to an importing country's economy and the well-being of its population if this risk is not known (Galli and Halle, forthcoming; Global Footprint Network, 2011). Trade analysis using Ecological Footprint accounting can, for example, identify:

- Which trading partner, in terms of the biocapacity it uses to produce resources, is most critical to a country's economic performance and to meeting the overall consumption demands of its residents?
- If these trade flows were to cease—for example, if Russia in the face of another low harvest were to again cut off exports of wheat—and a country forced to rely on its own biocapacity to meet domestic demand, to what extent could it do so?
- How large are demands from abroad on a country's domestic biocapacity, and how is this demand changing over time?

The answer to Giampietro and Saltelli's second question, about the risk of damage to ecosystems where resources are being produced, is no, this is not something Ecological Footprint accounting is designed to track – it only measures amounts of biocapacity available and amounts demanded, although the comparison between these two parameters can be used as proxy for the pressure humans placed on ecosystems. In conjunction with other indicators, however, Footprint assessments can help reveal the extent to which, for example, an exporting country's biocapacity is endangered (See the discussion earlier in the paper on the fragility of biocapacity).

In addition to the question of whether or not the Footprint has relevance for trade policy, Giampietro and Saltelli suggest that Footprint accounting has an anti-trade bias. They quote the Stiglitz commission's report (CMEPSP, 2009:71), stating that: "*The [Ecological Footprint] results are also problematic for measuring a country's own sustainability, because of the substantial anti-trade bias inherent in the Ecological Footprint methodology. The fact that densely populated (low biocapacity) countries like the Netherlands have [biocapacity] deficits, whilst sparsely populated (high biocapacity) countries like Finland enjoy surpluses [i.e. biocapacity reserves] can be seen as part of a normal situation where trade is mutually beneficial, rather than an indicator of non-sustainability.*"

Again, this statement confuses description with prescription. Ecological Footprint accounting can track biocapacity flows between countries, and the extent to which a country's demand exceeds its capacity to meet that demand, but nowhere does it state that this is desirable or undesirable, good or bad. Furthermore, while Ecological Footprint accounts assess only one dimension of sustainability, the size of a country's biocapacity deficit (or reserve) is a key parameter in determining a country's overall sustainability profile.

13. Conclusions

Ecological Footprint accounting is not theoretical ecology; it is resource accounting. Theoretical ecology, as the authors describe it, relies on estimates of the hypothetical "*natural density of the flow of interest in unaltered ecosystems.*" Ecological Footprint accounting, on the other hand, is based on a specific, well-defined research question about anthropogenic demand on the regenerative capacity of productive ecosystems. To answer this question, the metric tracks actual flows from real ecosystems as they currently exist today, rather than estimating hypothetical flows which may have little relationship to the rates at which resources are currently being regenerated. In doing so, Footprint accounting incorporates rather than ignores the influence of management practices and technology on productivity.

It is true that the Footprint "cannot handle the complexity of sustainability." But this is not "*because of its goal to deliver a simple*

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narrative (*a single number addressing all dimensions of sustainability*)." As explained, it is not the goal of the Footprint accounting to provide a comprehensive measure of sustainability. Instead, it measures only one key dimension, and the results need to be considered in conjunction with those of additional indicators if a fuller picture is desired.[11] The (Stiglitz et al., 2009), which Giampietro and Saltelli quote, acknowledges this as well: no single measure can do it all. In fact the Stiglitz Commission's 11th recommendation in the section entitled "Well-being is multi-dimensional" states that "sustainability assessment requires a well-identified dashboard of indicators."

In sum, the research question that Giampietro and Saltelli imply does or perhaps should underlie Ecological Footprint accounting is not the same as the one that actually drives the accounting. As a result, the "Ecological Footprint" that Giampietro and Saltelli criticize bears little resemblance to the Ecological Footprint as it is described and documented in numerous, openly available publications. What they seem to be describing is a hybrid pressure-plus-impact indicator, rather than solely a pressure (demand) indicator; one that is prescriptive, rather than descriptive; a metric based on the productivity of a hypothetical world rather than on the real world; one tasked with providing predictive results rather than descriptive historical data. Their metric aspires to be a complete measure of sustainability, aggregating a wide variety of different ecological dimensions, including the depletion of lithospheric resources such fossil fuels, into a single score; that is, an index rather than an indicator. In short, the preponderance of Giampietro and Saltelli's criticisms are aimed at an alternative conception of the Ecological Footprint.

The Ecological Footprint that is in widespread use today, which has been carefully reviewed and vetted by scientific bodies in a number of countries and embraced by numerous policy makers as an effective tool supporting their sustainability efforts, is a very different measure than the one that Giampietro and Saltelli are addressing. While surely subject to improvement, Ecological Footprint accounting provides effective, easily communicated and policy relevant measures of a key aspect of sustainability—that is, whether humanity is living within the planet's limited regenerative capacity, or exceeding it.

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9 April 2014

10 April 2014