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Questioning the Ecological Footprint

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ABSTRACT

In this perspective paper a critical discussion about the concept of the Ecological Footprint is documented based on 10 questions which are answered from critical and supporting points-of-view. These key questions are directed toward the underlying research objectives of the approach, a comparison with similar concepts, the quantification methodology and its accuracy, the characteristics of the observed flows, the role of scales and resolutions, the implementation of food security, the utility of the ecological footprint for society, the political relevance of the concept and the differences from other international indicator systems.

1. Introduction

Scientific debates are focal elements of progress in research and development of academic conceptions and methodologies. According to the strong epistemological tradition which demarcates science from other endeavors, the capacity to progress by successive refutations and rectifications is a focal element of scientific discussions. Although they are sometimes executed in an obstinate and less tolerant atmosphere, the outcome can be a productive “cross fertilization”, opening the objects of research for new aspects, setting new questions, demanding for adapted concepts and targets and widening the knowledge in the respective field of science.

Indicators provide aggregated and simplified information on phenomena which often are hardly directly determinable, and as such they are suitable objects of intensive debates: Their definitions, the relations to the indicandum, the elaborated methodology and its transparency, the respective measurements and collections, the produced results and their interpretations are often related with certain inaccuracies and uncertainties. Furthermore, the contextual extents of indicators as well as their degrees of aggregation provide a wide field of problems, challenges, potential ambiguities, normative loadings and, consequently severe discussions.

In the following, unusual article, a hopefully constructive step in the scientific debate about the Ecological Footprint is made: The paper is based on the exchange of several letters, replies and articles in which conceptual and methodological aspects of the Ecological Footprint have been discussed in this journal (see Giampietro and Saltelli, 2014a,b; Goldfinger et al., 2014; Lin et al., 2015 and additionally van den Bergh and Grazi, 2015). To avoid a long-term sequence of papers the authors agreed to produce this joint perspective article. It aims to shed light on the roots of ongoing critical

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discussions regarding the Ecological Footprint and its methodology. This has been boiled down to ten key questions by which we identify strengths and limitations of the Ecological Footprint from different perspectives. Therefore, in this article the authors do not agree with the overall contents; In the opposite, the paper is documenting basic disagreements. One perspective is offered by Mario Giampietro and Andrea Saltelli. The other perspective is presented by researchers associated with Global Footprint Network: David Lin, Mathis Wackernagel, Alessandro Galli, Elias Lazarus, and Steve Goldfinger. Both parties suggested five questions each to frame the discussion about the validity and the utility of Ecological Footprint accounting. Each perspective is offering their particular answers for all 10 questions.

This paper starts from a common point of departure. Both parties recognize that it is fundamental for policy formulation and monitoring to have a quantitative approach capable of measuring human demand on nature against nature's ability to provide ecological services. The position of Global Footprint Network is that Ecological Footprint Accounting adds up ecological services people demand in as far as they compete for biologically productive space.[3] According to this claim the Ecological Footprint can be compared against the available bioproductive area which provides these services – biocapacity for short (Borucke et al., 2013). Giampietro and Saltelli (2014a,b), on the contrary, argue that the claim of Global Footprint Network does not stand scrutiny and that the Ecological Footprint is not a quantitative approach capable of measuring human demand on nature against nature's ability to provide ecological services, and that the results generated by this methodology are not useful. This divergence of opinions led to the present paper.

The differences between the basic attitudes of the co-authors are already visible by focusing on the basic definitions:

The Footprint Network provides the following terminology: Ecological Footprint accounting answers the question: How much of the regenerative capacity of the biosphere is occupied by human demand? Humanity's Ecological Footprint is the sum of all biologically productive surfaces of the planet for which all the human demands compete. These biologically productive surfaces renew resources, provide services such as carbon sequestration, or accommodate urban infrastructure. Human demand can be a single activity, the consumption of one person, a city, a country or humanity as a whole. Ecological Footprints, or human demand (in a given year) is compared to the amount of resources and services that are generated by the biologically productive surfaces of the planet or a region (in that given year) – the biocapacity. Both biocapacity and Ecological Footprint are measured in hectare-equivalent units, namely global hectares. These are biologically productive hectares with world average productivity. Note that not only the Ecological Footprint but also biocapacity changes over time with shifting climate conditions, soil quality and management practice. As a consequence, the value of a global hectare also changes from year to year. Hence results are presented in constant global hectares, i.e., the value of a global hectare in a given year.

At the other side, Giampietro and Saltelli comment on the basic term of biocapacity with the following paragraph: What is called "biocapacity" in Ecological Footprint Accounting is better described as "agricultural productivity". It measures actual yields of biomass per hectare that are due to human manipulation of ecological processes (with no consideration for the damage to the environment) and massive injections of fossil energy based inputs (entailing the depletion of a non-renewable stock). Therefore, what is measured in the Ecological Footprint protocol under the label "biocapacity" is not an assessment of how much can be produced on this planet according to its ecological limits.

Basing upon these general contradictions, both parties suggested five questions each to frame the discussion about the validity and the utility of Ecological Footprint accounting. Both parties have answered all questions.

2. Key questions

1. What underlying research question does the Ecological Footprint address?[4]

Giampietro and Saltelli	Lin, Wackernagel, Galli Goldfinger, and Lazarus
The mathematical protocol developed by the Global Footprint Network (GFN) aims to assess *man's impact on the planet* and wishes to achieve this by aggregating across scales and compartments, while at the same time focusing on a subset of the relevant dimensions of man's impact. Thus the measures arrived at by the Global Footprint Network – the quantitative assessments labeled as "Ecological Footprint" and "Biocapacity" – have a purported resemblance with the regenerative and absorptive capacity of the biosphere but no descriptive power. A research question on man's impact on the planet is asked and left unanswered, while a full metaphorical apparatus is developed to communicate the result of this analysis as an overall measure of man's impact, such as the 'Earth Overshoot Day'. Stating that 'August 13 is Earth Overshoot Day 2015' (www.overshootday.org), and that in less than 8 months, Humanity exhausts Earth's budget for the year is a clear answer to the question of man's overall impact on the planet, but this number, precise to eight digits, is a misleading – an in a sense reassuring – non-being. Depending on what dimension of possibly irreversible impact of man on the planet is looked at this number could refer to a day located decades in the past (see answer 4).	Ecological Footprint accounting addresses one key question: *How much of the biosphere's regenerative capacity do human activities demand?* This measure can then be compared to the biosphere's available regenerative capacity. By doing so, the Ecological Footprint framework accounts for (1) the magnitude of humanity's physical metabolism and (2) the demand such metabolism places on the Earth's ecosystems. Thus, it captures a necessary, but not sufficient, condition for sustainability. The Ecological Footprint framework is not a measure of total human impact but a proxy for human pressure on ecosystems. In concept, the Ecological Footprint is the sum of ecosystem services used by humans, to the extent that these services occupy mutually exclusive, biologically productive area. These services include provision of resources, housing, infrastructure, and absorption of that population's waste, using prevailing technology and management practices (Wackernagel, 1991; Rees and Wackernagel, 1994; Wackernagel and Rees, 1996; Wackernagel et al., 2002). In current National Footprint Accounts (NFA), direct tracking of waste flows is limited to CO_2. By tracking and adding up human demands competing for biologically productive space, Ecological Footprint accounts incorporate both of Daly's sustainability principles (Daly, 1990) which stipulate that *within a closed system, the harvest rate should not exceed the regeneration rate and the waste production rate should not exceed the rate of assimilation.*

[3] For an introduction of the footprint methodology, see e.g. Borucke et al. (2013) and Wackernagel et al. (2014).

[4] Question formulated by the Footprint Network.

2. How is the research question underlying the Ecological Footprint relevant or irrelevant to policy concerns?[5]

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
When it comes to policy concern, one should bear in mind: (i) "make everything as simple as possible but not simpler" (Albert Einstein); and (ii) "all models are wrong, but some are useful" (George E.P. Box). Our criticism of the Ecological Footprint protocol moves from a critique of its implausible simplifications (e.g., for energy security the only biocapacity taken into account is land absorbing CO_2) to address the inadequacy of the construct to deal with the relevant subject matter. The questions addressed by the Ecological Footprint are relevant but the answers misleading (e.g., increasing ecosystem alteration is deemed positive for biocapacity). When dealing with policy concern, the combination of being relevant and scientifically wrong is unfortunate. The extraordinary success of the Ecological Footprint, its take up by a myriad of countries and well-intended organizations, and its frantic consumption by the media, raise deep concerns on the internal system of quality control of science – which is today in a status of deep crisis (Lancet, 2015; Nature, 2015; Ioannidis, 2014). As of today only a handful of practitioners have moved to context the veracity of the Ecological Footprint (see recent reviews in Blomqvist et al., 2013; van den Bergh and Grazi, 2015), and these critics have never reached neither the top mainstream scientific journals nor the media.	If we are to live within the ecological constraints of our planet, keeping track of the biophysical size of an economy – particularly compared to the size of supporting ecosystems – enhances effective policy development (Bullock et al., 2001). Assuming that human society cannot take more than the biosphere can renew without endangering its stability, any policy we implement should consider whether it deepens or alleviates society's resource dependence. Also, it may make sense for each society to set explicit goals about how much its economy should use compared to what ecosystems can renew. While most governments have not yet committed to meaningful and effective policies on consumption and resource efficiency, Ecological Footprint accounting has been incorporated into official initiatives of at least 12 national governments or intergovernmental agencies (e.g., Giljum et al., 2007; SENPLADES, 2010). It has been used to set targets and to guide major shifts in budgeting, sustainable investments, and policy (Whitby et al., 2014). Businesses and financial institutions have applied it, such as in the World Business Council for Sustainable Development's Vision 2050 Project. Additionally, civil organizations, such as the World Wide Fund for Nature International (WWF), use the Ecological Footprint accounts to represent human demand on natural systems.

3. If the research question underlying the Ecological Footprint has some relevance, are there more accurate methods available for answering this particular question?[6]

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
Yes: *Planetary Boundaries (Rockström et al., 2009a,b; Cornell, 2012; Wijkman and Rockström, 2012; http://www.stockholmresilience.org/21/research/research-programmes/planetary-boundaries.html) *Nature Index (Pedersen et al., 2013; Certain et al., 2011, 2013), that can be integrated into the UN System of Environmental-Economic Accounting; http://unstats.un.org/unsd/envaccounting/seea.asp *Ecological indicators from theoretical ecology, such as EMergy analysis (Odum, 1996; Brown and Ulgiati, 2004), Ascendency for aquatic ecosystems (Ulanowicz, 1996; Patrício et al., 2006), Ecosystem Integrity (Guntenspergen, 2014, Kay et al., 2001); *MuSIASEM to study the nexus between energy, food, water and land uses in socio-ecological systems and its relation to environmental impact (Giampietro et al., 2012, 2014; Madrid et al., 2013). The fact that none of the above methods offer the perfect tool to measure human demand on nature against nature's regenerative ability does not imply that the Ecological Footprint has comparable legitimacy and quality. In its insistence to capture the big picture with just one number the Ecological Footprint puts itself at odds with the community of scientists concerned with a responsible use of quantitative information in sustainability science.	Given the acknowledged lack of other comprehensive metrics in this domain, and the fact that Ecological Footprint accounts have been reviewed and validated by nearly a dozen government studies, these accounts represent, in our view, the best available systemic approximation of a human population's demand on nature. A unique feature of Ecological Footprint accounting is its ability to assess the size of the human enterprise against Earth's biological capacity, even over time. Complementary approaches exist, which confirm the risks of overconsumption (see also question 9). Planetary Boundaries (Rockström et al., 2009a,b; Steffen et al., 2015), for example, identify overuse in specific domains. However they do not provide an overall assessment of the ratio between human demand and earth's regenerative ability, nor show how this relationship changes over time, or show the regional distribution of overuse. Other approaches measure demand but are not able to identify limits. For example, the World Bank's monetary natural capital assessment provides a relative value of natural capital compared to other capital, but does not indicate whether the amount of natural capital is sufficient. Similarly, Material Flow Assessments track the weight of material flows, but this is not compared against any regeneration rate.

4. Given the quality and accuracy limitations of current Ecological Footprint results, is society better off without these results?[7]

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
The results provided by the ecological footprint are misleading and may result in harmful policies. According to the Ecological Footprint protocol replacing natural ecosystems with more productive human-managed vegetation would increase the biocapacity of our planet. The Ecological Footprint protocol suggests we are overshooting the carrying capacity of the planet by a mere 50%, but the quantity of nitrogen used in agriculture alone would already require 2.5 planets to be fixed by natural processes (let alone the generation of other valuable flows or the absorption of harmful pollutants.) The Ecological Footprint does not address the requirement of sink capacity for pollutants nor the supply capacity for liquid fuels. Other serious flaws have been pointed out in the journal PLoS Biology by Blomqvist et al. (2013) and by many others (for an overview see van den Bergh and Grazi, 2015).	The National Footprint Accounts, the main application of Ecological Footprint accounting, uses the standard international datasets and operates under the assumption that people would be better off with decisions fully informed by available empirical evidence of the biocapacity situation. Despite representing a conservative estimate of human demand on nature, current global and national accounts document significant biocapacity deficits (see Galli et al., 2014). If the Ecological Footprint truly is an underestimate, the implications suggest that contracting the human metabolism is necessary, and economic development strategies consistent with this material need should be adopted. Rejecting these results and continuing on current working assumptions, which largely ignore physical constraints, would make humanity worse off. Given that conservative results from the National Footprint Accounts (NFA) represent a minimum necessary condition, one could argue that sustainability policies based on current Ecological Footprint numbers may not be aggressive enough. However, current sustainability policies remain insufficient to address resource limitations and trends highlighted by Ecological Footprint accounts. For a detailed explanation on specific examples such as replacement of natural ecosystems with human managed systems such as cropland, and why this does not necessarily increase biocapacity, see Goldfinger et al. (2014).

[5] Question formulated by the Footprint Network.
[6] Question formulated by the Footprint Network.
[7] Question formulated by the Footprint Network.

5. What are the external referents used for quantitative assessments in Ecological Footprint Accounting and what is the accuracy of the measurement schemes used to quantify their relevant characteristics?[8]

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
This question is not a philosophical but technical one. Before undertaking any measurement, two pieces of information are needed: (i) expected characteristics of what has to be measured; and (ii) the accuracy of the measurement scheme. If we want to measure the height of a human being, we must be able to (i) recognize an instance of human being, i.e. what we want to measure; something with a height of 30 m (e.g., a statue) is not a human being even if it looks like one; and (ii) use a meter with an admissible accuracy. An accuracy of ±3 m is good for measuring the length of highways but not for measuring the height of human beings. What are the "expected characteristics" of the specific processes generating biocapacity that are measured by the Ecological Footprint? What is the error bar on the measurement of biocapacity expressed in global hectare equivalent? Is the accuracy of the assessment the same at the local, national and global level? The implications of these questions become clear in the answer to the next question 6.	The majority of data used in the Footprint accounts refers to annual produced quantities (tons per year), annual productivity (tons per hectare per year) and areas harvested/used for production of a given year (hectares) as reported by the UN. Currently, we cannot comprehensively assess the precision and accuracy of data compiled by UN statistics. Therefore, current National Footprint Accounts calculate results under the assumption that these data sources are reliable. However, discrepancies in trade statistics allow us to compare the degree to which a country's trade reporting matches its partners reporting for what should be identical transactions. These discrepancies give insight into potential noise in the data set. Significant difficulty remains in assessing the quality of input data; however verification reports have been performed by the national agencies (e.g., statistical bureaus) of several countries (e.g., France, Switzerland, Japan, and Luxembourg). In France, for example, the independent re-running of the national Footprint calculation with locally-sourced data has yielded results consistent with those generated by Global Footprint Network (1–4% difference). Additional assessments of NFA results continue to generate insights into potential improvement of the accounts. This includes moving toward reconciling balance-based NFAs with Multi-Regional Input–Output (MRIO), possibly leading to hybrid-MRIO based Footprint calculations (Weinzettel et al., 2014). Researchers are also refining the carbon Footprint calculation (Mancini et al., 2015).

6. When calculating Ecological Footprint and Biocapacity, is the measurement referring to the characteristics of a typology (which typology?) or to the characteristics of an instance? (An instance of what?)[9]

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
We answer this question with a metaphor about how to account for the biocapacity of a flow. Let's imagine one wants to calculate the "bio-capacity" required to obtain 1000 l of milk measured not in hectares but in number of cow-day equivalents. Let's assume that at world level there are three ways to supply milk: (A) producing 6–15 l/day per cow in production (to be reduced because of cow-days not in production); (B) producing 20–40 l/day per cow in production (ditto); (C) stock depletion (using stocks of long-conservation milk). Imagine to measure in a given year (2014) (i) the liters of milk supply in the world (590 billion = total liters); and (ii) the number of cow-days producing milk in the world (95 billion = total cow-days). The resulting ratio, 6 l/cow-day, reflects the *particular* situation in 2014 given by the relative importance of the three typologies A, B and C in providing the total supply, but does not provide an assessment of the "biocapacity" (expected characteristics of physical processes) required to produce 1000 l of milk. An assessment of 166.7 cow-days required for producing 1000 l of milk does reflect what happened in the year 2014 (an instance) but will not provide any information about the required "biocapacity" for producing 1000 l of milk on our planet in a sustainable way. An assessment of "biocapacity" would require a prior definition of the characteristics of the elements producing the flow. These characteristics determine their capacity to produce the flow in a sustainable way. This point is discussed in the next answer.	Ecological Footprint and biocapacity accounts measure bioproductivity expressed as the amount of global bioproductive area needed to supply a basket of services. The National Footprint Accounts use input data aggregated by year, and therefore are a time series record (1961–2011) of annual flows (Ecological Footprint and biocapacity). Biocapacity can change with environmental and managerial conditions and reflects current conditions as opposed to a theoretical productivity in the absence of human influence. Biocapacity accounts start with actual land areas (ha), which are then weighted by their relative global bioproductivity (global hectares). Footprint accounts start with material flows such as cereals, vegetables, milk, wood, CO_2 emissions, etc. Then the amount of actual land area needed to generate these flows is calculated. Just as with biocapacity, these areas are expressed in a common measurement unit, global hectares. This is done by calculating the area, at world average productivity, needed to generate these flows. Stocks are not tracked by Footprint accounts. For example, the calculation of the Ecological Footprint (or biocapacity requirement) of milk in 2014 starts with milk produced in 2014 (not stocks). Using the production flow, we then calculate the total amount of equivalent bioproductive land required for the production of this milk. The Footprint of milk is spread across grazing land (to provide food for milk-animals), cropland (again to provide food for milk-animals), built-up land (to provide supporting infrastructure), and forest land (to sequester CO_2 emitted through electricity and fossil fuel use during the production process). For the consumption Footprint, we add to this production number the import and subtract the exports.

[8] Question formulated by Giampietro and Saltelli.
[9] Question formulated by Giampietro and Saltelli.

7. Ecological Footprint Accounting methodology generates a unique set of quantitative assessments obtained combining together measurements referring to processes taking place at different scales. This unique set of quantitative assessments is supposed to be equally useful for agents operating at different scales – e.g. farms, cities, provinces, nations, macro-regions, and the planet. What are the main benefits and the main limitations of this approach?[10]

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
The Ecological Footprint protocol is measuring *flows* without making a distinction among different typologies of elements producing the flows. Using the metaphor of milk production described in the previous question 6 we distinguish: Type A: flow in steady-state based on natural processes. Cows producing milk without drugs with a life expectancy of over 15 years are the external referents to be used to measure natural biocapacity; Type B: flow determined by human technology powered by non-renewable resources. Cows forced to produce more milk with hormones and fossil-energy based unhealthy diets should not be included in measurements of natural biocapacity; Type C: non-renewable flow. Depleting stocks of long-conservation milk has nothing to do with biocapacity. Summing indiscriminately the different sources of milk and cows-days in 2014 generates a number that is completely useless for policy. The resulting value of 6 l per cow-day does not provide any relevant information for individual dairy farmers (when deciding how to produce milk: type A or B?), regional governments regulating milk production, or national governments making scenarios of the environmental impact of milk production. Moving out of the metaphor of milk production, an increase in land productivity in agriculture based on the massive depletion of "long conservation stocks of fossil energy" should not be interpreted as an increase in ecological biocapacity. All sums elaborated by the Ecological Footprint system of accounting are obtained by mixing together characteristics of instances belonging to different typologies (liters of milk from cows of Type A, Type B and from stocks), without even specifying the relative size of these instances in the mix.	Ecological Footprint accounting provides a framework for organizing information. At each spatial scale, whether global, national, individual, or a single activity, appropriate data for these accounts is required. Simmons et al. (2000) describe two methods to derive NFAs. The first approach follows a bottom-up approach and attempts to account a complete set of consumed items, and determines the Ecological Footprint of each of these using Life Cycle Assessment (LCA). Accuracy here depends on the completeness of the set, and the accuracy of the individual LCAs. Given a robust set of input data, this method can be reasonably accurate and is generally better suited for high-resolution specific accounts, such as those at the individual or activity level, but suffers from data availability at larger scales. Global Footprint Network uses a second method to produce the NFAs. This method is a top-down approach which uses national aggregate input data on production, trade flows, and consumption. (For a full listing of inputs, see Kitzes and Justin, 2009). For practical implementation, regional or world average data is substituted when country specific data is not available. The accuracy and reliability of accounts following this method are highest at global level and in countries with robust national statistics. For finer scale accounts such as those of a province, either appropriate province level data is required or lower resolution national data must be scaled down. The latter would result in decreased accuracy. For end users, it can be useful to track Footprint accounts through time and in different spatial contexts, from household to global. Following the principles listed in answer 1, heads of a household may make decisions based on a particular biocapacity budget, just as a city or a nation could.

8. Ecological Footprint Accounting measures the biocapacity required for energy security as the land requirement required to absorb the CO_2 emissions. But then why does it not adopt the same logic for calculating the biocapacity required for food security – e.g. measuring the land required to absorb human dejections and food waste – rather than the land required to produce food?[11]

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
As explained by Georgescu-Roegen (1975) (building on the work of Lotka and Odum) a society metabolizes matter and energy in two different forms: (i) endosomatic flows – nutrients contained in food metabolized **inside** the human body; (ii) exosomatic flows – energy carriers and minerals metabolized and transformed under human control but **outside** the human body. This second metabolism requires the use of technology (exosomatic devices). Both types of metabolism require biocapacity for the supply of the input flows (to produce foods eaten by the population and to produce energy carriers and materials used by society) and for the sink-capacity of waste flows (to absorb dejections and emissions). However, when dealing with the stability of endosomatic metabolism (the requirement of food) the Ecological Footprint protocol measures the requirement of biocapacity by looking only at the supply side (land required for agricultural production). On the contrary when dealing with the stability of the exosomatic metabolism (the requirement of commercial energy) the Ecological Footprint protocol measures the requirement of biocapacity by looking only at the sink side (land required for absorbing CO_2). This is logically inconsistent. Moreover, the Ecological Footprint protocol cannot indicate whether a given land use can or cannot be counted as contributing to sustainability. For example, the land area required for disposal of waste, such as landfills and associated infrastructures may indicate a sustainability problem, as many populations living close to a landfill can testify, when the landfill is unsafe and unhealthy. This is the same issue flagged in questions 6 and 7 above.	Ecological Footprint accounts do not, nor are they intended to measure energy security. Neither do they track stocks (such as the availability of fossil fuels). They only look at the demand for the annual capacity to produce renewable resources and assimilate waste. This logic is followed consistently for CO_2, food waste, or human dejections. In the case of CO_2, this service is waste assimilation. It is a competing demand on biocapacity and therefore can be added up to other demands. Also, to meet the minimum condition for sustainability in a closed system, in any given year waste should not be produced faster than it is assimilated. Ecological Footprint accounting therefore considers fossil fuel only from the perspective of its demand on waste assimilation capacity (one aspect of the overall biocapacity). The demand on nature imposed by waste food and human dejections is not discretely tracked by the Ecological Footprint, but is captured within two components of the Ecological Footprint, the carbon Footprint and the Built-up land Footprint. The carbon Footprint captures the production of CO_2 released during the energy intensive collection and processing of this waste, and the Built-up Footprint captures the land demand for infrastructure, which includes areas appropriated for waste disposal such as landfills and associated infrastructure.

[10] Question formulated by Giampietro and Saltelli.
[11] Question formulated by Giampietro and Saltelli.

9. Can the assessments generated by Ecological Footprint Accounting methodology define: (i) whether the flows considered in the quantitative assessment are in steady-state or referring to transitional states (i.e. flows obtained by stock depletion and filling of sink); (ii) how much these flows are beneficial to the economy; and (iii) how much these flows are damaging ecological funds; why should assessments of exported (or imported) biocapacity be relevant?[12]

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
Assessments of Ecological Footprint and Biocapacity are used to calculate the surplus or deficit of biocapacity determined by the terms of trade. However, we should not be surprised to find countries that externalize their requirement of bio-capacity (using someone else's land) thanks to favorable terms of trade. Countries trade exactly to exchange what they have in excess with something they need. Sparsely populated countries with an abundance of natural resources are likely to export their bio-capacity in exchange for capital intensive or information intensive goods. At the level of the whole planet the effect of trade is zero (it is a zero sum game). At the country level, the Ecological Footprint does not provide relevant information about local environmental impacts – what types of biocapacity are required to generate the traded flows. Addressing this issue would require the use of spatial analysis and addressing explicitly the issue of multi-scale analysis. Since by definition the Ecological Footprint cannot say whether a country's input in biocapacity is achieved at the expenses of another country's irreversible depletion, the information of the Ecological Footprint cannot be used to target virtuous bilateral policies but only the generically single out for blame countries importing biocapacity.	(i) Conceptually, Ecological Footprint accounts are capital maintenance accounts in that they analyze flows from the perspective of whether they lead to net change in stocks (depletion and/or accumulation). In other words, they calculate the flows required to avoid a change in stocks. All demand and all regeneration are expressed as flows – in consistent units – contrary to the claims of Giampietro and Saltelli (Borucke et al., 2013). These flows represent humanity's demand on and nature's supply of a given set of ecological services. (ii) Given the biophysical limits of the planet, and the finite ability of the environment to regenerate resources, the human economy is a subsystem which resides within the system of the environment. Sustainable development requires that these flows (as described in answer 1) meet minimum material conditions of sustainability. When these conditions are not met, the system is in ecological overshoot. Both transitional flows and steady-state flows play a part in the accounts and as currently measured, continued overshoot leads to a depletion of ecological assets. Such depletion, while not assessed by Footprint accounts, could include loss of groundwater, soil, fish stock, forest biomass, or carbon accumulation in the atmosphere. (iii) Specific assessments of damage to ecological assets can give useful information about their ability to maintain current levels of production flows in the future. These lines of research are important and still contain significant knowledge gaps. As stated in question 1, Ecological Footprint accounting aims to answer a core question related to resource production and consumption. It is related to, but does not answer specific questions related to ecosystem damage. NFAs track incoming and outgoing flows but do not inform whether specific flows of income can be maintained in the long-run. Comparisons of these incoming and outgoing flows indicate where unsustainable imbalances occur.

10. How is the Ecological Footprint Accounting similar or different from other international metrics/indicator systems?[13]

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The Ecological Footprint is different from other international metrics or indicators because it violates simultaneously: (i) semantic rules – the assessment of what is proposed as biocapacity. The assessment provided by the Ecological Footprint protocol should be called bio-contingency or agricultural productivity instead, as the capacity of land to produce and absorb flows used by humans depends mainly on the use of human technology and the amount of fossil energy used as inputs at a given time point and location. By measuring what is happening today (bio-contingency, including the over-exploited cow and the stock of milk in the metaphor discussed in the answer 6) rather than what is sustainable (the healthy cow), the Ecological Footprint makes a disservice to the ecological community; (ii) common sense rules – the more ecological systems are altered the higher becomes their biocapacity; (iii) formal rules of accounting – dimensional inconsistency in the proposed equations, where flows of CO_2 (dimensions kg/s) are offset by stocks of land (dimensions kg/m^2); (iv) formal rules of sensitivity analysis – the continuous shift of quantitative assessments across scales makes the quantitative output very fragile due to cumulated uncertainty in the conversion factors and the rounding of the values (Saltelli et al., 2008). Finally, the Ecological Footprint is also different from the other measures listed in the answer to question 3 by its ambition to reach the bottom-line with a single number, such as in its "Earth Overshoot Day" campaign. In relation to this point we can only recall the quote of Einstein: "make everything as simple as possible, but not simpler".	Ecological Footprint Accounting and the main output, the National Footprint Accounts are unique in three ways • Consumption (Ecological Footprint) can be compared to a biophysical budget limitation (biocapacity). • Data is aggregated to a single comparable unit of biocapacity (gha). • Time series of flows are provided (1961–2011). Additionally, this is a subject with potential for a long discussion. To orient the discussion, it is important to make a distinction between accounts and composite indices. The Ecological Footprint framework provides accounts. *Accounts* add components together using a common unit of measure. Other examples of accounts are GDP, greenhouse gas inventories (with CO_2 equivalents as unit), water accounts. Accounts can therefore compare, for instance income with expenditure, as both are also using the same measurement unit. Therefore, flows of CO_2 emission of an activity can be contrasted with flows of annual CO_2 sequestration of an area of land. Both are measured in the same units (kg/year). *Composite Indices* aggregate data across different domains which may not have equivalent units, and subjectively assign weights to the various domains to determine their relative value. Such indices score a situation according to a defined set of rules and based on expert judgment. They are therefore outside of the realm of pure scientific inquiry. Table 1 compares accounts with aims similar to those of Ecological Footprint accounting: quantifying human use of natural capital. Regarding the breaking of common sense rules, readers are encouraged to review Goldfinger et al. (2014) for a description of how altering ecosystems does not necessarily determine an increase in biocapacity.

[12] Question formulated by Giampietro and Saltelli.
[13] Question formulated by the Footprint Network.

11. Summarizing the discussions.

Giampietro and Saltelli	Lin, Wackernagel, Galli, Goldfinger and Lazarus
We acknowledge the good intentions behind the Ecological Footprint and the commitment of its proponents. We advise against its use because the Ecological Footprint metric is affected by serious methodological flaws: (1) The Ecological Footprint equates "agricultural productivity" with "biocapacity". Agricultural productivity is presently boosted by reliance on non-renewable fossil energy (stock depletion) and monocultures (associated with soil erosion, pesticides, phosphorous and nitrogen leaking into the water, biodiversity loss). This increase in productivity carries an ecological impact, which is not captured by the Ecological Footprint accounting; (2) The Ecological Footprint misleads on energy security. Several planets would be needed to generate agro-biofuel (Giampietro and Mayumi, 2009) matching present energy consumption. The Ecological Footprint ignores this because it considers only the requirement of land for absorbing CO_2 and not for producing fuels. (3) The Ecological Footprint ignores that a given forest area can absorb emissions only during growth. When the forest becomes mature additional forest area is needed. Therefore the assessment of land demand should not be given in "number of hectares" but as "a quantity of hectares which is a function of time"; (4) The Ecological Footprint neglects scales. At the local scale some societies can import "ghost land" because other societies export it. At the global level this type of accounting generates a "zero sum game". In fact, when ignoring the area required for carbon sink, between 1961 and 2001 the ecological footprint of the planet for the other inputs remained basically the same in spite of doubling world population, 6 times increase in economic activity and 2.5 times increase in food production (Giampietro and Saltelli, 2014a).	Using the Ecological Footprint to derive policies requires a proper understanding of the question that the tool addresses. Otherwise one may not be able to draw valid conclusions from the results. To increase clarity, discussions as conducted in this paper about the method and possible misunderstandings are essential. They hopefully improve researchers' understanding of the actual method, identify research areas for improvements, and highlight areas where a communication deficit may have led to misinterpretations. For this discussion, we therefore started by identifying the purpose and scope of this accounting tool. Ecological Footprint Accounts ask, "*In a given year, how much of the biosphere's regenerative capacity did human activities demand?*" Therefore, it does not measure, for instance, energy security, but may provide relevant insights into the topic. Furthermore, we emphasized the following: *The Ecological Footprint is not a measure of human impact, nor is it a predictive measure of the sustainability of specific management practices. It is an accounting system that compares human demand on Earth's ecosystems to what these ecosystems are able to renew.* Given this scope and knowledge, Ecological Footprint accounts should be used as a necessary but not sufficient minimum reference framework that approximates all of humanity's demands on nature that compete for biologically productive area.

3. Conclusions

Due to the selected form of this paper, these short conclusions for sure will not include any valuation of the answers and statements. Much more, we hope that some urgent challenges, limitations, and misunderstandings of the Ecological Footprint approach have become clearer, as well as the potential value added from this approach. The respective conclusions can be drawn by the reader. Concerning the future development of the footprint approach and its applications, the critical remarks are understood as demands for clarification, improvement, future development and information to critically ensure the users about the potentials and limitations of the concept.

Global Footprint Network's researchers acknowledge that several aspects of the Footprint are misunderstood and possibly based on outdated versions of the method. Therefore, establishing clarity around Footprint-related definitions is paramount to guide future scientific debate and provide meaningful applications. As part of this effort, the Footprint community should aim to improve communication around what the Ecological Footprint can and cannot do. The authors also acknowledge that methodological advances are needed in a few key areas of Footprint accounting (see for instance Kitzes and Justin, 2009). To progress from the points of departure in this paper and continue methodological advances, the authors extend a call for open collaborations with academic researchers who aim to improve quantitative approaches to measure human demand on nature against nature's ability to renew for the formulation and monitoring of sustainability policies.

On a more general level, the discussion held in this paper elucidates some general problems of environmental indication and especially of sustainability representations. As sustainable development is an extremely complex process it is not possible to represent its multiple features with one indicator set alone. Thus also the footprint cannot indicate sustainability as a whole, but it can look at some attributes of sustainability from a very distinct perspective. Caveats as to the limited scope of any measurement can be assigned to any sustainability indicator set. Hence, more indicators need to be integrated in any meaningful analysis.

Another conclusion arising from the experience of this paper is the visible demand and necessity of discussions and arguments about indicator qualities, contextual limitations and problems. There are several severe conceptual and methodological challenges which all actors have to face in indicator development. As stated in the introduction – a basic element of scientific progress is the capacity to settle disputes via scientific arguments.

As such, and given the current proliferation of indicators and the information overload policy makers have to face, research is needed in exploring the synergies among sustainability indicators and to evaluate how they can complement each other (and jointly reduce their own limitations) in monitoring sustainability. An assessment of the linkages between Ecological Footprint accounting and other measures such as ecosystem services or wealth accounting (see also other measures listed in question 3 and Table 1), could be highly relevant for the readership of the *Ecological Indicators* journal as well as for all other actors interested in both indicators' development and use.

In the end, we all, editors, critical and defending authors celebrate this attempt to bring key questions to the table and to wrestle with clarifying constructively and sincerely the different perspectives. We have succeeded if we provided input for the entire community to better understand the potential utility and limitations of an approach like Ecological Footprint accounting. While we are still far away from agreement in how to quantify or even clearly define a sustainable human economy, it is worthwhile pursuing the search for solutions through the use of sustainability indicators, even if potentially elusive.

The authors on both sides do agree that exercise like this one and the format of this paper can represent an effective method to enhance the quality check on the development of new scientific approaches. In fact, it is important to avoid ending up in scientific disputes that can be described as 'scientists throwing numbers at each other'. The present paper will hopefully contribute useful

Table 1
By Lin, Wackernagel, Galli, Goldfinger and Lazarus: Comparing the footprint accounts with similar approaches.

Concept	Footprint and biocapacity	Planetary Boundaries	Mass Flow Analysis (also called 'material footprint')	Carbon Footprint	WAVES/Genuine Saving	Inclusive Wealth	Genuine Progress Indicator (GPI or ISEW)	HANPP	TEEB
Organizations	Global Footprint Network	Stockholm Resilience Centre	Wuppertal Institute	IEA/IPCC	World Bank	UN University	Herman Daly, John & Cliff Cobb, Redefining Progress, others	Systems Ecology – Austria	UNEP
What research question is being answered?	How much of the regenerative capacity of the biosphere is occupied by human demand? (Plus, where does demand originate, and how is the biocapacity distributed on the planet?)	What are planetary boundaries, and for each one of them, how close is humanity to those limits?	How much mass moves through an economy?	How much CO_2 from fossil fuel is released within a country? Also by a lifestyle or activity.	How much net wealth does a country have? How does it change year to year? (focus on natural capital)	How much wealth is in a country? How does it change year to year?	What is the net income of a country, including non-market benefits, and excluding defensive expenditures?	How much net primary production is appropriated by human economies from the ecosystems within their region?	What is the economic value of ecosystem services?
How is this question relevant to understanding a country's (or other entity's) risk and opportunity exposure?	In the 21st century, biocapacity is increasingly a limiting factor for the human economy. It is essential to know how much you have, how much you use, and what the trends are.	Makes a scientific global case for a number of dimensions. Adds credibility to the possibility of global overshoot. May not be easily applicable at local scale. Not clear what trade-offs are among boundaries.	More mass flow is a proxy for the overall amount of resource being used.	Future climate treaties could put a limitation on this emission, through prices, or regulations. To set targets and monitor progress, metrics are needed.	Is overall wealth (measured in monetary value) building up per capita? If not, this is a risk to income generation in the future.	Is overall wealth (measured in monetary value) building up per capita? If not, this is a risk to income generation in the future.	GPI adjusts GDP for aspects that subtract from wellbeing, and adds those that are missing, making the measure a more realistic assessment of what the true annual income of a nation is.	How intensively are they using their own ecosystems? Higher usages, in combination with high net imports, put countries at risk. High usages could also lead to degradation.	How big are ecological benefits compared to economic benefits? Are there hidden costs that overshadow benefits? Are there both economically and ecologically better options for development?
Metric	Global hectares	kg/yr/kg/yr	kg/year	kg/year	$	$	$	kg biomass/year	$/yr
Key websites	www.footprintnetwork.org Wackernagel et al. (2014)	Rockström et al. (2009a,b)	www.wupperinst.org www.materialflows.net Fischer-Kowalski et al. (2011)	www.Ipcc.ch Hertwich and Peters (2009)	See website for reports	www.inclusivewealthindex.org See website for reports	www.rprogress.org/sustainability_indicators/genuine_progress_indicator.htm	Krausmann et al. (2013)	See website for reports
Strengths	Provides the bottom-line answer to a central question: Is there enough biocapacity to maintain the metabolism of the economy? Area is relatively easy to understand - it is like a farm. Has been tested by 12 national governments.	Each one of the planetary boundaries can easily be communicated and are known to most publics. Can build on independent robust scientific assessments in each domain.	Kg easy to understand, directly links to tracked mass flows of categories. Some statistical offices now track mass flows.	There is a scientific effort behind carbon accounting. Public is starting to be more sensitive to basic climate science.	Dollars speak loudly to traditional economic analysts.	Dollars speak loudly to traditional economic analysts.	Dollars speak loudly to traditional economic analysts. GPI relates clearly to GDP, possibly the most prominent policy indicator.	Biophysical assessment.	Powerful case stories. Applicable to business and policy contexts.
Weaknesses	Many details could be improved beyond the current accounts that use 6000 data points per country and year. The accounts, however, are constantly being refined. There is currently no direct link to financial figures, which makes it harder to communicate to finance oriented audiences. However, numbers can be interpreted for them.	Some boundaries are global (CO_2), others are local (water, nitrogen). Difficult to understand trade-offs among them. Difficult to apply at sub-planetary scale.	Mass flow accounts are at the basis of Footprint accounts. But it is less clear what question they answer. One kg of gravel has different demand on nature than one kg of wood. (Apart from weight, in what way are they ecologically equal?) How do mass flows link to supply? Which mass flows are included and which ones not, and why? While having good material statistics is fundamental, result interpretation (or how to use them to guide policy) is not as obvious.	CO_2 in isolation is hard to tackle since self-interest for those reducing their emission is not obvious or may be absent. Just focusing on CO_2 may detract from all other environmental pressures.	Dollars are unstable predictors of the future. Prices can fluctuate by magnitudes. They only show current human preferences in the market, not ecological necessities.	Dollars are unstable predictors of the future. Prices can fluctuate by magnitudes. They only show current human preferences in the market, not ecological necessities. Results are counterintuitive, and suggest that natural capital has extremely low value.	Dollars are unstable predictors of the future. Prices can fluctuate by magnitudes. They only show current human preferences in the market, not ecological necessities, or resource limits. What is added or subtracted from GDP to get GPI can be arbitrary, a problem which could be overcome with clear and widely accepted accounting standards for GPI calculations.	Tool cannot establish clear ecological limits to demand. Does not deal with trade.	Not comprehensive yet. Also mostly based on financial value assessments.

elements to help the reader form her/his own opinion on the merits of and the need for an Ecological Footprint.

References

Blomqvist, L., Brook, B.W., Ellis, E.C., Kareiva, P.M., Nordhaus, T., Shellenberger, M., 2013. Does the shoe fit? Real versus imagined ecological footprints. PLoS Biol. 11 (11), e1001700, http://dx.doi.org/10.1371/journal.pbio.1001700.

Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J.C., Wackernagel, M., Galli, A., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecol. Indic. 24, 518–533.

Brown, M.T., Ulgiati, S., 2004. Emergy and environmental accounting. In: Cleveland, C. (Ed.), Encyclopedia of Energy. Elsevier, New York, NY, USA.

Bullock, H., Mountford, J., Stanley, R., 2001. Better Policy Making. Centre for Management and Policy Studies, Cabinet Office, London, UK.

Certain, G., Skarpaas, O., Bjerke, J.-W., Framstad, E., Lindholm, M., et al., 2011. The nature index: a general framework for synthesizing knowledge on the state of biodiversity. PLoS ONE 6 (4), e18930, http://dx.doi.org/10.1371/journal.pone.0018930.

Certain, G., Nybø, S., Barton, D., et al., 2013. The SEEA Experimental Ecosystem Accounting framework: Structure, Challenges, and Links with the Nature Index. In: Working document prepared for the Expert Group Meeting: Modelling Approaches and Tools for Testing of the SEEA Experimental Ecosystem Accounting, 18–20 November 2013, UN Headquarters, New York, USA.

Cornell, S., 2012. On the system properties of the planetary boundaries. Ecol. Soc. 17 (1), r2.

Daly, H.E., 1990. Towards some operational principles of sustainable development. Ecol. Econ. 2, 1–6.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting: state of the art and reliability across sources. J. Ind. Ecol. 15 (6), 855–876, http://dx.doi.org/10.1111/j.1530-9290.2011.00366.x.

Galli, A., Wackernagel, M., Iha, K., Lazarus, E., 2014. Ecological Footprint: Implications for biodiversity. Biological Conservation 173, 121–132.

Georgescu-Roegen, N., 1975. Energy and the economic myth. South. Econ. J. 41 (3), 347–381.

Giampietro, M., Aspinall, R., Ramos-Martin, J., Bukkens, S., 2014. Resource Accounting for Sustainability: the Nexus between Energy, Food, Water and Land Use. Routledge.

Giampietro, M., Mayumi, K., 2009. The Biofuel Delusion: The Fallacy of Large-scale Agro-biofuel Production. Earthscan.

Giampietro, M., Mayumi, K., Sorman, A.H., 2012. The Metabolic Pattern of Society: Where Economists Fall Short. Routledge.

Giampietro, M., Saltelli, A., 2014a. Footprint to nowhere. Ecol. Indic. 46, 610–621.

Giampietro, M., Saltelli, A., 2014b. Footprint facts and fallacies: a response to Giampietro and Saltelli (2014) footprints to nowhere. Ecol. Indic. 46, 260–263.

Giljum, S., Hammer, M., Stocker, A., Lackner, M., Best, A., Blobel, D., Ingwersen, W., Naumann, S., Neubauer, A., Simmons, C., Lewis, K., Shmelev, S., 2007. Scientific assessment and evaluation of the indicator "Ecological Footprint". Project Z 6–FKZ: 363 01 135, Final Report. German Federal Environment Agency, Dessau.

Goldfinger, S., Wackernagel, M., Galli, A., Lazarus, E., Lin, D., 2014. Footprint facts and fallacies: a response to Giampietro and Saltelli (2014) footprints to nowhere. Ecol. Indic. 46, 622–632.

Guntenspergen, G.R. (Ed.), 2014. Application of Threshold Concepts in Natural Resource Decision Making. Springer, p. 327.

Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environ. Sci. Technol. 43 (16), 6414–6420.

Ioannidis, J.P., 2014. How to make more published research true. PLoS Med. 11 (10), e1001747.

Kay, J.J., Allen, T., Fraser, R., Luvall, J.C., Ulanowicz, R.E., 2001. Can we use energy based indicators to characterize and measure the status of ecosystems, human, disturbed and natural? In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A., Mayumi, K. (Eds.), Advances in Energy Studies: Exploring Supplies, Constraints and Strategies. SG Editoriali, Padova, pp. 121–133.

Kitzes, J., Wackernagel, M., 2009. Answers to common questions in ecological footprint accounting. Ecol. Indic. 9 (4), 812–817.

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. PNAS 110 (25), 10324–10329, http://dx.doi.org/10.1073/pnas.1211349110.

Lancet, Editorial, 2015. Rewarding true inquiry and diligence in research, 385., pp. 2121.

Lin, D., Wackernagel, M., Galli, A., Kelly, R., 2015. Ecological footprint: informative and evolving – a response to van den Bergh and Grazi (2014). Ecol. Indic. 58, 464–468.

Madrid, C., Cabello, V., Giampietro, M., 2013. Water-use sustainability in socio-ecological systems: a multi-scale integrated approach. BioScience 63 (1), 14–24.

Mancini, et al., 2015. Ecological footprint: refining the carbon footprint calculation. Ecol. Indic., http://dx.doi.org/10.1016/j.ecolind.2015.09.040.

Nature, 2015. Misplaced faith, Editorial, June 2, The public trusts scientists much more than scientists think. But should it?, vol. 522., pp. 6.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley & Sons.

Patrício, J., Ulanowicz, R., Pardal, M.A., Marques, J.C., 2006. Ascendency as ecological indicator for environmental quality assessment at the ecosystem level: a case study. Hydrobiologia 555, 19–30.

Pedersen, B., Nybø, S., Skarpaas, O., 2013. Ecological framework for the Nature Index. A more rigorous approach to the determination of reference values and selection of indicators – NINA Minireport 442., pp. 28.

Rees, W., Wackernagel, M., 1994. Ecological Footprints and appropriated carrying capacity: measuring the natural capacity requirements of the human economy. In: Jansson, A., Hammer, M., Folke, C., Costanza, R. (Eds.), Investing in Natural Capital,. Island Press, Washington DC.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009a. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 (2), 32 [online] http://www.ecologyandsociety.org/vol14/iss2/art32/.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., 2009b. A safe operating space for humanity. Nature 461 (7263), 472–475.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Salsana, M., Tarantola, S., 2008. Global Sensitivity Analysis – The Primer. Wiley.

SENPLADES (Secretaría Nacional de Planificación y Desarrollo), 2010. National Plan for Good Living 2009–2013, English summary available at: http://www.planificacion.gob.ec/wp-content/uploads/downloads/2012/08/versi%C3%B3n-resumida-en-ingl%C3%A9s.pdf.

Simmons, C., Lewis, K., Barrett, J., 2000. Two feet-two approaches: a component-based model of ecological footprinting. Ecol. Econ. 32 (3), 375–380.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science, 1259855.

Ulanowicz, R.E., 1996. Trophic flow networks as indicators of ecosystem stress. In: Polis, G., Winemiller, K. (Eds.), Food Webs: Integration of Patterns and Dynamics. Chapman-Hall, New York, pp. 358–368.

van den Bergh, J., Grazi, F., 2015. Reply to the first systematic response by the Global Footprint Network to criticism: A real debate finally?, http://dx.doi.org/10.1016/j.ecolind.2015.05.007.

Wackernagel, M., Cranston, G., MoralesF J.C., Galli, A., 2014. Chapter 24: ecological footprint accounts: from research question to application. In: Atkinson, G., Dietz, S., Neumayer, E., Agarwala, M. (Eds.), Handbook of Sustainable Development: Second Revised Edition. Edward Elgar Publishing, Cheltenham, UK, ISBN:13: 978-1782544692.

Wackernagel, M., 1991. Land Use: Measuring a Community's Appropriated Carrying Capacity as an Indicator for Sustainability"; and "Using Appropriated Carrying Capacity as an Indicator, Measuring the Sustainability of a Community". In: Report I & II to the UBC Task Force on Healthy and Sustainable Communities, Vancouver.

Wackernagel, M., Rees, W.E., 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, Gabriola Island, Canada.

Wackernagel, M., Schulz, B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002. Tracking the ecological overshoot of the human economy. Proc. Natl. Acad. Sci. U.S.A. 99 (14), 9266–9271.

Weinzettel, J., Steen-Olsen, K., Hertwich, E.G., Borucke, M., Galli, A., 2014. Ecological footprint of nations: comparison of process analysis, and standard and hybrid multiregional input–output analysis. Ecol. Econ. 101 (May), 115–126, http://dx.doi.org/10.1016/j.ecolecon.2014.02.020.

Whitby, A., Seaford, C., Berryal, C., 2014. BRAINPOoL Project Final Report: Beyond GDP – From Measurement to Politics and Policy. In: BRAINPOoL deliverable 5.2. A collaborative programme funded by the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No. 283024, Available at: http://www.brainpoolproject.eu/wp-content/uploads/2014/05/BRAINPOoL-Project-Final-Report.pdf.

Wijkman, A., Rockström, J., 2012. Bankrupting Nature: Denying Our Planetary Boundaries: A Report to the Club of Rome. Routledge.