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# Footprints to nowhere

Mario Giampietro[a,c], Andrea Saltelli[b,*]

[a] Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[b] Institute for the Protection and Security of the Citizen (IPSC), The European Commission, Joint Research Centre, TP 361, 21027 Ispra, VA, Italy
[c] Catalan Institution for Research and Advanced Studies (ICREA), Passeig Lluís Companys, 23, 08010 Barcelona, Spain

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ABSTRACT

Crisp numbers make it to the headlines. However, it is unlikely that a single crisp number can capture a complex issue, such as the analysis of the sustainability of human progress both at the local and the global scale. This paper tackles this standard epistemological predicament in relation to a media-friendly model of man's impact on Nature: the Ecological Footprint (EF). The claim made by the proponents of this analytical tool is that EF makes it possible to check "how much is taken" by the economic process versus "how much could be taken" according to ecological processes. In this paper we argue that the ecological footprint assessment – purportedly useful as an argument against the idea of perpetual growth – is fraught with internal contradictions. Our critical appraisal is based on the lack of correspondence between the semantics – the claim about what the EF accounting does – and the syntax – the EF protocol of accounting that should deliver the purported output. We critically examine the various assumptions used in the approach, showing that the EF is in contradiction with its stated purposes and would lead to paradoxes if its prescriptions were used for policy making. We also contend that the laboriousness of EF computation protocols contrasts with its ultimate fragility. In fact the estimate of carbon footprint due to energy production is what determines the assessment of the planet's deficit of virtual land. We show that this estimate cannot be defended in light of the assumptions and simplifications used for its construction. Our conclusion is that the EF does not serve a meaningful discussion on the modeling of sustainability, and that the same media-friendly narrative about the Earth Overshot day is in the end reassuring and complacent when considering other aspects on man's pressure on the planet and its ecosystems.


## 1. Introduction

Crisp numbers make it to the headlines. Thus a poignant way to warn against perpetual economic growth and the plundering of natural resources is by stating '*Our planet is already 50% over-exploited*'. At least, this is the claim made by the Global Footprint Network (GFN) on its website. According to its designers, the Ecological Footprint provides a useful narrative to assess man's impact on earth, be it the lifestyle of a person, the economy of a country or the state of the planet.

Stating a concept under the aegis of a number also makes good marketing, as known to authors of books such as '*29 Leadership Secrets*'. The success of the Ecological Footprint concept is likely associated to the strong social demand for such a product. The proponents of the Ecological Footprint (EF) analysis have successfully filled a gap in the market by designing a straightforward numerical indicator whose simplicity appeals to the media and general public and whose mild verdict has found ready approval with the political establishment. Unfortunately, the simplifications adopted to reach a wide audience come at the cost of the logical coherence of the proposed analytical tool. Indeed, we demonstrate in this paper that the Ecological Footprint, presented as an argument against the idea of perpetual economic growth, depicts in fact a much rosier state of affairs than an ecological analysis would warrant.

The Ecological Footprint analysis has earlier been subject to severe criticism from within the scientific community. This critique has centered on a series of specific logical inconsistencies in the EF protocol and shortcomings in the indications it provides (e.g., Bastianoni et al., 2012; Fiala, 2008; Haberl et al., 2001; Lenzen et al., 2007; Ponthiere, 2009; Tabi and Csutora, 2012; van den Bergh and Grazi, 2010; van den Bergh and Verbruggen, 1999; Wiedmann and Barrett, 2010; Wiedmann and Lenzen, 2007).

In the time window the paper was being reviewed the debate has developed and reached a new high thanks to a paper in PLOS (Blomqvist et al., 2013a). The footprint community reaction was also published (Rees and Wackernagel, 2013) as well as the authors counter conclusion to this (Blomqvist et al., 2013b).

In this paper we go a step further to the same diligent analysis of Blomqvist et and co-workers, and examine the overall weakness of the approach from an epistemological perspective, that is:

* Corresponding author. Tel.: +39 0332789686
*E-mail address:* andrea.saltelli@jrc.ec.europa.eu (A. Saltelli).

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(i) the lack of congruence between the original narrative of the Ecological Footprint and the protocol presently proposed for its quantification; (ii) the consequent incongruence of the quantitative indications provided by the EF index; and (iii) the flaws in the pre-analytical assumptions.

To this purpose, we first present in Section 2 the cultural premises in the field of theoretical ecology against which Wackernagel and Rees developed the original narrative of the EF concept in the early 90s (Rees and Wackernagel, 1994; Wackernagel and Rees, 1996). Then, in Section 3, we analyze the metric currently used in the Ecological Footprint analysis, the factors determining the requirement (human appropriation) and supply (biocapacity) for food and useful biomass, and the carbon footprint. In Section 4 we examine the conceptual flaws in the EF protocol in relation to the "non-energy related" biocapacity. In Section 5 we target the protocol for the quantification of the "energy related" biocapacity measured in the EF protocol in terms of carbon footprint. Finally, in Section 6 we place our findings in the context of the pitfalls and challenges of the production and use of quantitative science for governance and argue that in the present situation of Post-Normal Science (high stakes, urgent decisions, and large doses of uncertainty in complex societal and ecological settings) practitioners and stakeholders alike need to be vigilant that the quality of scientific work is not compromised by the high pressure from society for simple answers and straightforward numbers.

## 2. The original narrative used to frame the Ecological Footprint Analysis by simplifying theoretical ecology's concepts

In this section we briefly describe the scientific settings and cultural context against which Wackernagel and Rees developed their Ecological Footprint in the 1990s (Rees and Wackernagel, 1994; Wackernagel and Rees, 1996). Well before the introduction of the Ecological Footprint, many theoretical ecologists had made significant progress in the development of quantitative analyses to characterize the impact of human activity on the integrity of ecological processes. Much of this work focused on developing a quantitative representation of the interaction between complex socio-economic systems (human processes) and ecological systems (ecosystem processes). With this interaction taking places simultaneously across two different spatio-temporal scales, scientists inevitably struggled with serious epistemological problems. Not surprisingly then the quantitative approaches put forward all emphasized a careful pre-analytical and theoretical discussion of the nature of the investigated systems (e.g., Margalef, 1968; Odum, 1971, 1983, 1996; Ulanowicz, 1986, 1995, 1997) and converged toward a similar rationale: natural ecosystems are the result of autopoiesis (self-organization stabilized by informed autocatalytic loops) taking place under a set of biophysical constraints – i.e. thermodynamic laws.

This rationale allowed the definition of sets of expected characteristics for different typologies of ecosystems – a natural state for the studied typology. For example, we can now effectively talk of a trophic structure of a tropical forest, a savannah or an aquatic ecosystem. We can also define expected relations between the sizes of individual functional compartments (e.g., carnivores, herbivores) within a selected typology of ecosystem. In the same way, we can predict the volume of water evapotranspirated per unit of standing biomass in given typologies of terrestrial ecosystems. It is within the general context of non-equilibrium thermodynamics and autopoietic systems that concepts such as "ecosystem health" (Cairns et al., 1993; Schaeffer et al., 1988; Waltner-Toews et al., 2008) or "ecosystem integrity" (Kay and Schneider, 1992; Woodley et al., 1993; De Leo and Levin, 1997) become meaningful.

Indeed, the existence of expected benchmarks for typologies of *healthy* ecosystems makes it possible to detect situations of ecosystem stress and/or lack of integrity of ecological elements (i.e., elements operating outside their natural configuration). Within this common frame, various quantitative methods of formalization of indices of stress have been proposed, including:

- *Em*ergy analysis, useful to assess the degree of environmental loading –i.e. assessing the densities of flows per hectare determined by human colonization against the expected densities of flows per hectare associated with the characteristics of ecosystem typologies (Odum, 1971, 1996);
- Indicators based on network theory, such as the concept of ascendency that aims at quantitatively describing the growth and development (biocomplexity) of an ecosystem as a whole – looking at the expected sets of quantitative characteristics of the relations parts/whole (Ulanowicz, 1986, 1995, 1997);
- Extended input/output analysis (embodied analysis), studying the interface of energy and material flows between ecosystems and economies (Herendeen, 1981, 1998);
- Indicators assessing the disturbance to terrestrial ecosystems induced by agricultural production using thermodynamic analysis of water flows per unit of standing biomass (Giampietro and Pimentel, 1991).

All the above approaches share a common semantic framing: (i) they assume that it is possible to define an expected set of characteristics for known typologies of healthy (i.e., undisturbed) ecological systems; (ii) these benchmarks are then used as a yardstick against which the degree of disturbance found in specific situations (instances of disturbed ecosystems) is measured. Thus, these quantitative analyses are based on two numerical assessments of "flow" characteristics (e.g., kg of biomass of a given element per ha/year) that are associated with the identity of ecosystems. These two assessments refer to two clearly defined *external referents*: (i) the expected characteristics of natural flows in a given typology of undisturbed ecosystem ($\Phi_{NAT}$) and (ii) the measured characteristics of actual flows in a given instance of altered ecosystem, i.e., the system to be assessed for ecological compatibility ($\Phi_{ACT}$).

For instance, an expected flow rate of biomass in a healthy ecosystem ($\Phi_{NAT}$) can be contrasted against a measured, actual flow rate of biomass in the system under analysis ($\Phi_{ACT}$). In this way one can obtain a quantitative indication of the degree of alteration ("stress") by measuring the discrepancy between the actual, measured state ($\Phi_{ACT}$) and the expected state for that typology of ecosystem ($\Phi_{NAT}$). Or, alternatively, starting from the size of a particular element of an ecosystem, known to perform a given function, one can calculate the corresponding size of ecosystem that would be required to respect the natural pattern of organization (like estimating the body size of a pre-historic man from the size of the skull). Quantitative applications of this approach are illustrated in Box 1 and have been explained in detail elsewhere (Giampietro and Pimentel, 1991).

When first presenting their innovative approach – the ecological footprint analysis – Rees and Wackernagel relied on the scientific premises just described by referring to the concept of *natural capital* (Rees and Wackernagel, 1994). They built on the idea put forward by Ecological Economics (Daly, 1990) using the concept of *strong sustainability*: Given that manufactured capital cannot substitute for natural capital (manufactured capital and natural capital are complements of each other) anyone interested in sustainability should have a method to monitor the preservation and reproduction of natural capital in relation to the flows of natural resources and ecological services that the manufactured capital cannot supply. Rees and Wackernagel (1994) formulated it this way:

> 'The dominant vision of the global economy is one in which "the factors of production are infinitely substitutable for one another" and in which "using any resource more intensively guarantee an increase in output" (...). In short, prevailing economic mythology assumes a world in which carrying capacity is infinitely expandable (Daly, 1986). By contrast the ecological perspective holds that some biophysical resources and processes are irreplaceable... Carrying capacity is ultimately constrained by the ability of self-renewing natural capital to continue providing ecological goods and essential life-support services.' (Rees and Wackernagel, 1994, p. 379, emphasis added)

So in the original narrative of the Ecological Footprint analysis proposed in the 1990s; Wackernagel and Rees (1997, p. 4) state:

> The Ecological Footprint is "the direct biophysical measurement of renewable natural capital" defined as all those components of the ecosphere and the structural relationships among them, whose organizational integrity is essential for the continuous self-production of the system itself."

To better clarify this point Rees and Wackernagel (1994) ideated an ecological narrative of sustainable use of resources in which humans should be "living on the interest" of the natural capital. To define this situation they recall the "Hicksian view" of sustainability (see Gowdy, 2005) – the use of resources should be limited by the available biocapacity.

## 3. The present protocol for Ecological Footprint analysis adopted by the Global Footprint Network does not match the semantics of the original narrative

### 3.1. Possible contradictions between EF's programme and EF's practice

Using the terms proposed in the most recent publication of the Global Footprint Network (Borucke et al., 2013) the metric of the Ecological Footprint analysis is based on the calculation of two terms: (1) the *ecological footprint*, human appropriation, or demand on the biosphere based on the actual level of resource consumption; and (2) the *biocapacity* or "biosphere's regenerative capacity" to supply these resources. Whenever the ecological footprint of a system (an economy, a nation) is larger than its biocapacity we have a situation of "unsustainability" or "overshoot", which is flagged by a deficit in virtual global land. This deficit occurs when the virtual global land that would be required to meet the system's demand is larger than the actual supply of "biosphere's regenerative capacity" (expressed in virtual global land). Using the narrative illustrated earlier this deficit indicates that what is taken from nature is more than the 'interest' that the available natural capital can give.

A concrete example of this approach is illustrated in Fig. 1, adapted from Ewing (2010), which shows the changes in the Ecological Footprint of our planet (the overall demand for "biosphere's regenerative capacity") expressed in "global hectares" equivalent over the last 45 years. If we make a distinction between the two main components making up the total *requirement* of resources and ecological services, that is the non-energy-related requirement (requirement for crop, grazing, forest and built-up land and fishing grounds) and the energy-related requirement (measured as carbon footprint), we see that:

- The non-energy-related requirement of biocapacity for the supply of food and other useful biomass consumed by humankind, has remained substantially unchanged during these 45 years; whereas
- The energy-related requirement of biocapacity (the carbon footprint) has been linearly increasing in time. Note that this assessment only takes into account the biocapacity needed to absorb the $CO_2$ emissions related to energy consumption and does not take into account the biocapacity needed to obtain the energy supply.

To better illustrate this observation, we have partially rotated the original figure (from Ewing et al., 2010) shown in the lower-left corner of Fig. 1. Thus, according to the results shown in Fig. 1, an increased consumption of fossil energy drives the steadily growing carbon footprint

According to an analysis of the Millennium Ecosystem Assessment (MEA, 2005) in the last 45 years the human population has

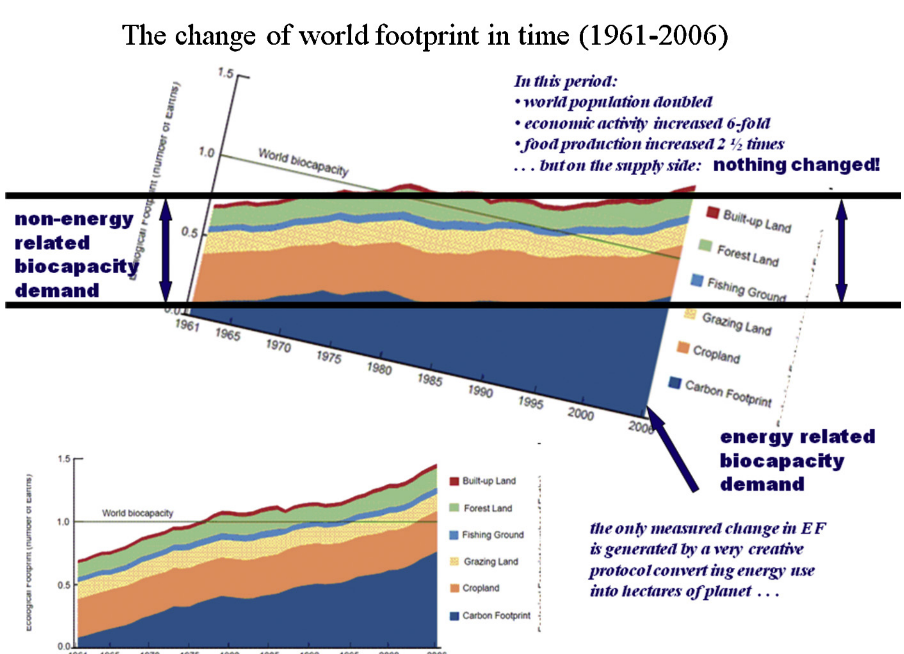


**Fig. 1.** The changes in the Ecological Footprint of the planet between 1961 and 2006. Adapted from Ewing (2010).

**Box 1: Using the expected hierarchical structure of terrestrial ecosystems (examples adapted from Giampietro and Pimentel, 1991)**

Given the natural hierarchical structure of a healthy forest ecosystem, we find that a tiger in that forest has an expected density $\Phi_{NAT}$ of 0.00002 kg/m$^2$. That is, in their natural environment top carnivores require about 50,000 m$^2$ (5 ha) of forest area per kilogram of body mass. This is equivalent to an average of 4 tigers per 50 km$^2$ (5000 ha). This large area is needed to support the activity of plants, which are required to fuel (directly and indirectly) the herbivores and lower-level carnivores that are eventually hunted by top carnivores.

Consider now the situation of four tigers, of about 250 kg each, confined to a zoo, an artificial habitat of 10,000 m$^2$ (1 ha). This translates in an actual density $\Phi_{ACT}$ of 0.1 kg/m$^2$. The ratio $\Phi_{ACT}$ /$\Phi_{NAT}$ indicates that the density in the zoo is 5000 times higher than the natural density. In other words, the four tigers would require 5000 ha ($5 \times 10^6$ m$^2$) of forest ecosystem if they were to be supported by natural processes. The large discrepancy between $\Phi_{NAT}$ and $\Phi_{ACT}$ points at a total lack of ecological integrity in the zoo system. Indeed, the zoo does not produce the specific energy input (meat) needed to feed the tigers, but rather buys it from the market. The quantitative mismatch between: (i) $\Phi_{NAT}$ – the expected value of the density of a given metabolic element (a tiger) in the typology of natural ecosystem considered (0.00002 kg/m$^2$); and (ii) $\Phi_{ACT}$ – the actual value of the density of that given metabolic element in the zoo (0.1 kg/m$^2$) can be used to measure how much the system is operating outside its natural range of values. In this example we could say that each tiger has an "ecological footprint" of 5000/4 = 1250 virtual hectares of her original natural ecosystem.

In the same way we find that plant biomass production in high external input monocultures (e.g., seven tons of cereals per hectare) is very "unnatural" compared to the net primary productivity of wild grain species in natural prairies (in the order of kg per hectare). More in general, one can use the concept of *Environmental Loading* (proposed by the school of H.T. Odum) to assess, according to the typology of natural ecosystem under analysis, the ratio between the density of a given flow resulting from human colonization (e.g., 250 kg of nitrogen fertilizers applied per hectare in a crop field) and the corresponding expected flow density (e.g., 50 kg/ha of nitrogen fixed in the soil by natural processes).

doubled, food production has more than doubled, and the size of the world economy has increased 6 fold. MEA's conclusion is that the explosion of human activity in the last 45 years has dramatically increased the stress on world ecosystems through a profound change in land use (deforestation), a massive increase in use of technological inputs in agriculture, and widespread pollution due to the massive release of old (e.g. GHG) and new chemical substances (e.g. new classes of pesticides and chemical substances). The first of the four main findings listed in the document of synthesis of the Millennium Ecosystem Assessment states:

> "Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fiber, and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth" (MEA, 2005).

Yet, according to the Ecological Footprint analysis (Fig. 1), apart from the $CO_2$ emission increasingly overshooting the absorption capacity, nothing much happened over the past 45 years in relation to the non-energy-related ecological footprint. Hence, we are left to conclude that according to this assessment over the past 45 years the carrying capacity of this planet steadily rose, since the increase in the consumption of food and biomass did not cause any harm to the natural capital of our planet. It is worth recalling that the original aim of the ecological footprint accounting was exactly to prove that this is impossible.

In the following sections we analyse these points. We start with a brief illustration of the structure of the protocol proposed by the Global Footprint Network (GFN) and then we move on to the specifics of the assessment of each one of the factors making up the requirement and the supply of the "biosphere's regenerative capacity".

### *3.2. The Global Footprint Network's formal protocol for Ecological Footprint analysis*

It is no easy job to define *the* EF protocol of analysis. In fact, the protocol is continuously being adapted in response to criticism (see e.g. Kitzes et al., 2009). To the best of our knowledge, the latest patches to the 2010 methodology (Ewing et al., 2010) have already been described by Borucke et al. (2013).

The accounting framework proposed by the GFN has the goal of quantifying and comparing: (i) the annual requirement of "biosphere's regenerative capacity" (the Footprint); and (ii) the annual supply of "biosphere's regenerative capacity" (the Biocapacity). Thus, we must generate two distinct assessments (Wackernagel et al., 2002):

(1) The Ecological Footprint of Consumption (the requirement), which depends on the consumption of food, energy, other biomass, and infrastructures of a given social system. This requirement can be assessed at different scales, a city, a given country (national footprint accounting) or the entire humankind, and refers to a given year, *given the prevailing technology and resource management of that year*.
(2) The available biosphere's regenerative capacity (the supply of biocapacity), which measures the amount of biologically productive land and sea area available to provide food, other biomass, energy and infrastructures by a given social system. The ecological budget of regenerative capacity refers to a given year, *given the prevailing technology and resource management of that year*.

As explained on the website of the Global Footprint Network:

> "This accounting system tracks, on the demand side (Footprint), how much land and water area a human population uses to provide *all it takes from nature*. This includes the areas for producing the resource it consumes, the space for accommodating its buildings and roads, and the ecosystems *for absorbing its waste emissions* such as carbon dioxide. These calculations account for each year's prevailing technology, as productivity and technological efficiency change from year to year. The accounting system also tracks *the supply of nature*: it documents how much biologically productive area is available to provide these services (biocapacity). Therefore, these accounts are able to compare human demand against *nature's supply of biocapacity*".
>
> (http://www.footprintnetwork.org/en/index.php/GFN/page/footprint_basics_overview/, the emphasis in the quote is ours)

As evidenced by the claim above, the present Ecological Footprint Analysis stillmakes reference to the original ecological narrative of natural capital introduced in the 1990s. We will argue below that none of the statements emphasized in italics above is semantically valid with regard to the practice of the Ecological Footprint Analysis. In fact, 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 in which humans rely only on a supply of input flows *without stock depletion* (no plundering of oil stocks, soil, underground water reservoirs, deforestation, destruction of biodiversity) and a sustainable recycling of flows *without filling of sinks* (no accumulation of greenhouse gases in the atmosphere and no pollution of air, water and soil).

Although Rees and Wackernagel (1994) acknowledge the importance of this reference state (as discussed they refer to it as a state in which humans are "living on the interest" of the natural capital) and the need of assessing a corresponding level of resource use – what they call the "Hicksian/sustainable" use of biocapacity – the proposed protocol of Ecological Footprint analysis uses a sole set of numbers – expressed both in global hectares or hectares of "biosphere-capacity equivalent" referring to an existing altered state. This problem has been flagged by Bastianoni et al. (2012) as a discrepancy between the "indicandum" (a sustainable ecological state) and the proposed indicator (an assessment based on prevailing conditions).

*3.2.1. The Ecological Footprint of consumption (requirement of biocapacity)*

The assessment of the ecological footprint of consumption can be divided into two main components as illustrated earlier in Fig. 1:

(1) The *non-energy-related* biocapacity required by the economy of the system under analysis. This is determined by five factors referring to five categories of land-uses: (i) agricultural production (crops); (ii) livestock production (terrestrial animal); (iii) fish production (aquatic animal); (iv) wood production (forest); (v) built-up surfaces (cities and infrastructures) and is expressed in hectares of "land equivalent" associated with the specific purpose.
(2) The *energy-related* biocapacity required by the economy of the system under analysis. In the original EF analysis this requirement referred to the energy inputs needed by society (Rees and Wackernagel, 1994). However, in the more recent versions of national footprint accounting (e.g., Borucke et al., 2013) this component is reduced to a mere assessment of the resulting carbon footprint and measured in an area equivalent (virtual global hectares) that, according to the assumptions of the protocol, would be required to neutralize the amount of $CO_2$ produced.

The assessment of each of the various factors making up these two components is obtained using a standard approach: First one calculates the ecological footprint of the appropriated production ($EF_P$), which is then adjusted to account for the effect of trade.

The ecological footprint of the appropriated production is defined as follows (Ewing et al., 2010) for each of the considered products:

$$EF_p = \frac{P}{Y_n} \times YF \times EQF$$

where $P$ is the amount of product produced (or carbon dioxide emitted); $Y_N$ is the national average yield for P (or the carbon uptake capacity); YF is the yield factor between the local and world average productivity (it varies by country); EQF is the equivalence factor used to correct the assessment of the area of a specific land use type into units of world average biological productive areas. This factor will be discussed in detail below, for the moment it is enough to say that in practical terms it has a negligible impact on the overall assessment. $EF_P$ is the resulting estimate of a *virtual area* of biosphere's regenerative capacity, measured in global hectares, which, according to the protocol, measures *nature's demand of biocapacity* – what would be needed to stabilize the production/consumption of the considered products and the absorption of $CO_2$.

For example, to find the ecological footprint of the appropriated production ($EF_P$) of crops at the national level we have to proceed as follows:

(1) $P$ – physical flow of local production (e.g., kg of crops per year);
(2) $Y_N$ – local yield (the average yield of crops expressed in kg/ha);
(3) YF – the ratio between the yield of crops in a country ($Y_N$) and world average yield of crops ($Y_W$). For example, Ewing et al. (2010) report a ratio of 2.2/1 for Germany and 0.3/1 for Algeria;
(4) EQF correction factor (having the goal to correct this value by supposedly making some sort of reference to ecological processes as discussed later on).

The result ($EF_P$) does *no longer* refer to the *actual local altered state*, nor does it refer to actual processes taking place at the global scale. In fact this assessment is obtained by dividing the amount of locally produced products (assessed at the local scale) by the corresponding world average of crop yield ($EF_P = P/Y_N \times YF = P/Y_N \times Y_N/Y_W = P/Y_W$), an assessment referring to the global scale corrected by a quality factor.

Then, to obtain the Ecological Footprint associated to a pattern of consumption, one has to account for the effect of trade in case part of the local production is exported or part of the local consumption is imported. Also in this case the protocol is straightforward (Borucke et al., 2013, p. 523):

> In order to keep track of the biocapacity – both direct and indirect – needed to support people's consumption patterns and to properly allocate the Footprints of traded goods to final consumers, the National Footprint Accounts use a consumer-based approach; for each land use type, the Ecological Footprint of consumption (EFC) is thus calculated as:

$$EF_C = EF_P + EF_I - EF_E$$

where $EF_P$ is the Ecological Footprint of production and $EF_I$ and $EF_E$ are the footprints embodied in imported and exported commodity flows, respectively.

Thus, the requirement of biocapacity for exported products is not accounted for in the Ecological Footprint of a given system, whereas the requirement of biocapacity for imported products is included. The need of accounting for imported products explains why the GFN protocol has opted for the solution of weighting all locally consumed products by the average world yields. In this way one avoids the complication of tracking the different countries from which the imported products are derived in order to be able to use the specific yields for each one of the imported flows.

*3.2.2. The available biocapacity (the supply)*

The biosphere's regenerative capacity (biocapacity – the proposed proxy for natural capital) available to the economy of the system under analysis is obtained by assessing the hectares of "land equivalent" for five different land-use categories: (i) cropland; (ii) grazing land; (iii) marine/inland water area; (iv) forest area (for biomass production and for absorbing $CO_2$); (v) infrastructure area. The protocol of calculation of the supply of biocapacity for these five different land use categories is similar to the one used to calculate the demand. The overall biocapacity is the sum of the biocapacities calculated for each of the five land use categories:

$$BC = \Sigma BC_{LUi} = \Sigma(A_{LUi} \times YF_{LUi} \times EQF_{LUi})$$

where $BC_{LUi}$, BioCapacity referring to land use *i*; $A_{LUi}$, area of land use *i* (at the local scale); $YF_{LUi}$, the yield factor, i.e., the ratio between the yield (or absorbing capacity) of the land use at the local level ($Y_N$) and the corresponding world average ($Y_W$); $EQF_{LUi}$, the equivalence factor (having the goal to correct this value by supposedly making some sort of reference to ecological processes as discussed in the next section).

*3.2.3. Logical inconsistencies in the protocol for the supply of biocapacity*

The application of the above protocol for the assessment of the supply of biocapacity generates some logically inconsistent results for the various land-use categories:

*3.2.3.1. Assessment of the Biocapacity of cropland.* The first two factors used to determine the supply of biocapacity for cropland, i.e., the area in crop production ($A_{LUcrop}$) and the crop yield in relation to the world average yield ($YF_{LUcrop}$), do not bear any relation to ecological characteristics. Probably, in response to the criticism received on this point (e.g. van den Bergh and Verbruggen, 1999) a third factor was included in the protocol, the $EQF_{LUi}$, with the following explanation: "The rationale behind the EQF calculation is to weight different land areas in terms of their inherent capacity to produce human useful biological resources" (Borucke et al., 2013). This explanation has little bearing on what in done in practice in the protocol. In fact the protocol uses suitability indexes calculated from Global Agro-Ecological Zones model combined with data on the actual areas of cropland, forest land, and grazing land from FAOSTAT (http://www.fao.org/nr/gaez/en/). These indexes provide a characterization of available land resources based on climate, soil and terrain conditions relevant to agricultural production. They indicate *for specified management conditions and levels of inputs* (i.e., possible different levels of alteration of ecological processes) feasible agricultural land-use options and quantify expected production of cropping activities relevant in the specific agro-ecological context. Thus, this information assesses to what extent different land types can be *altered* using fertilizers and other management techniques to boost yields. Hence, the use of this equivalence factor does not address the original criticism to the protocol. It is unclear why providing averages values based on information about "how much" different types of terrestrial ecosystem can be altered by using technology should be relevant in relation to the goal of the ecological footprinting. If the goal is to assess the natural capital available one has to know the typologies of terrestrial ecosystems that were altered for the purpose of local food production (what type of local ecosystem was replaced by crop fields?) and the impact of existing agricultural land use on soil and local biodiversity. So in our view this protocol of assessment of biocapacity for cropland does not carry any relevant information about quantity, level of preservation or damage to local natural capital available for crop production. Moreover the use of the EQF factor implies negligible corrections when considering global assessments. The decisive factors in the assessment of biocapacity in the protocol remain "the area in production" and "the average productivity of crop fields". These two factors, in turn, depend on the local and global demographic pressure and, above all, on the technology used in agricultural production at the local and global level – i.e. the quantity of technical inputs such as fertilizers, pesticides, machinery used in agriculture (Giampietro, 1997). 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".

Recall that the biocapacity should measure the quantity of natural capital according to the original Ecological Footprint narrative and a large biocapacity is supposed to be positive in ecological terms. Instead, according to the EF protocol, the larger is the local alteration of bio-geochemical cycles (human intervention), the larger is the calculated Biocapacity of the local system.

The same observation can be made at the global level. The significant increase in average global crop productivity over the last 45 years can be attributed to intensification of synthetic fertilizer use (MEA, 2005). The yearly consumption of synthetic nitrogen fertilizer at world level was less than 1 million tonnes in the 1920s, over 60 million tonnes in the 1980s (Smil, 1987), and about 100 million tones in 2009 (EFMA, 2009). The introduction of high-yielding varieties and, later, genetically modified organisms also contributed to raising yields (MEA, 2005). This massive alteration of geochemical cycles has been detrimental to our natural capital but allowed a simultaneous increase in the "consumption" (e.g., food consumption rose 2.6 fold over the last 45 years) and the "supply" of biosphere capacity (e.g., food production increased by 2.6 fold over the last 45 years). This simultaneous increase in requirement and supply of biosphere capacity would represent exactly *the unlimited expansion of carrying capacity* claimed by the neo-classical economists and so fervently denied by Rees and Wackernagel (1994). It also explains why, when applying the GFN protocol nothing much happened over the past 45 years in relation to the non-energy-related ecological footprint (Fig. 1).

Although the Ecological Footprint analysis was conceived to fight the dominant economic vision on the global economy by focusing on "the ecosystemic roles, the ultimate value, the necessary minimum quantities or even the remaining volumes of relevant capital stocks" (Rees and Wackernagel, 1994, p. 379), the protocol employed by the GFN perceives the intensification in use of pesticides, synthetic fertilizers and GMO-crops as an improvement. As observed by van den Bergh and Verbruggen (1999) the capital sin of the Ecological Footprint accounting is to completely ignore the distinction between sustainable and non-sustainable land uses.

*3.2.3.2. Assessment of forest biocapacity for wood production (not including carbon footprint).* A similar problem is found in the analysis of the supply of biocapacity in relation to wood production:

> "The replacement of ancient woodlands with monoculture forests through clear cutting is defined by the Swedish Forestry Agency as the single largest threat against biodiversity in Swedish forests. . . In Sweden's Footprint accounts the higher yields of these monocultures will increase the national

biocapacity, and thus lead to a favourable comparison between Footprint and biocapacity".

"As indicated in Table 1, 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". (Lenzen et al., 2007)

The results provided by the protocol clash with the EF's original claim: "The EF is 'a planning tool that can help to translate sustainability concerns into public action'" (Wackernagel and Rees, 1996).

It should be noted that Bastianoni et al. (2012) after highlighting this problem (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) suggest to use a correction factor considering such a difference in the assessment of both biocapacity for crops and wood production. However, the proponents of the ecological footprint were so far unable to provide a method for assessing the biocapacity of natural processes.

*3.2.3.3. Assessment of marine/inland water biocapacity (fishing and aquaculture).* This is "one of the most complex" calculations present in the National Footprint Accounts (Ewing et al., 2010, p. 9). Its semantic is explained by Borucke et al. (2013) as follows: "The fishing ground is calculated based on the annual primary production required to sustain a harvested aquatic species". Then, an equivalence factor (EQF) is calculated such that "the amount of calories of salmon that can be produced by a single global hectare of marine area will be equal to the amount of calories of beef produced by a single global hectare of pasture" (Borucke et al., 2013, p. 523).

The final assessment follows from elaborated calculations regarding the fraction of harvested biomass on net primary productivity, the expected relation across trophic levels, and the fraction of by-catch, averaged over 19 different aquatic species. However, as we will discuss in Section 4, it is unclear why this final number should have any relevance (for whom?) at either the local level (why should a salmon fisher be concerned with an assessment expressed in global hectares equivalent of virtual grazing area) or at the global level (the ratio between the demand and supply of biocapacity always remains more or less constant anyway). Here as elsewhere the EF's modelling complexity seems to obfuscate rather than illuminate.

*3.2.3.4. Assessment of cropland biocapacity for infrastructure.* The area in buildings and infrastructures is calculated from the area actually in use for these purposes ($A_{\mathrm{LUbuilt}}$). Then this area is multiplied by the yield factor for crop land (local crop yield in relation to the world average crop yield) ($\mathrm{YF}_{\mathrm{LUcrop}}$) because cities tend to sit on cropland (Wakernagel et al., 2002). Still, the logic of why the supply of biocapacity used for building and infrastructure should be measured in area of crop-equivalent is not entirely clear. According to the protocol the overall balance of this specific land use is apparently not very relevant for the EF accounting. In fact, the ecological footprint (demand) of this land use tends to be equal to its biocapacity (supply), potential differences only being generated by the yield factors of crops and the difference between export and imports. It makes one wonder why this land use category (representing a negligible fraction of total land) is included in the protocol in the first place.

*3.2.3.5. Assessment of grazing biocapacity.* This assessment involves an elaborate calculation. As explained by Borucke et al. (2013, p. 524, emphasis added):

"The grazing land calculation is the most complex in the NFAs and significant improvements have taken place over the past seven years... However, as the yield of grazing land represents the amount of above-ground primary production available in a year with no significant prior stocks to draw down, and given the fact that soil depletion is not tracked by the Ecological Footprint methodology (Kitzes et al., 2009), an eventual overshoot for this land use type still cannot be shown."

Also for this assessment demand and supply of biocapacity are the same by default as acknowledged by the EF's Authors in the previous quote.

*3.2.3.6. Assessment of forest biocapacity for carbon footprint.* This category of assessment is in our view the most problematic of the protocol in terms of assumptions. It refers to what was called in the original framework of the EF analysis the "energy-related" biocapacity (the biocapacity required to stabilize in time the production and consumption of energy inputs – Rees and Wackernagel, 1994). In the later protocols, however, the original relation to energy security has disappeared; now the protocol considers only a virtual area, measured in global hectares, of "uptake land to accommodate the carbon footprint" (Borucke et al., 2013, p. 525). The formula for the carbon footprint ($\mathrm{EF_C}$) is:

$$\mathrm{EF_C} = \left[\frac{P_\mathrm{C} \times (1 - S_\mathrm{Ocean})}{Y_\mathrm{C}}\right] \times \mathrm{EQF}$$

$P_\mathrm{C}$, annual anthropogenic emission of carbon dioxide; $S_\mathrm{Ocean}$, the fraction of anthropogenic emission captured by oceans in a given year; $Y_\mathrm{C}$, the annual rate of carbon uptake per ha of world average forest land; EQF, the correction factor for the land use category forest.

Although it is extremely hard, if not impossible, to put reliable numbers into this equation – especially the assessment of $S_\mathrm{ocean}$ is everything but easy (McKinley et al., 2011; Wanninkhof et al., 2012) – the GFN issues no warning that the implementation of this equation may be very problematic. Another interesting point is the footnote related to the use of forest land (the factor $Y_\mathrm{C}$) in this equation:

"Global Footprint Network has not yet identified reliable global data sets on how much areas are legally protected and dedicated to long-term carbon uptake. For this reason, current National Footprint Accounts do not include a carbon uptake category within the biocapacity calculation." (Borucke et al., 2013, p. 525, emphasis added)

That is, this protocol assumes that: (i) to get and use energy inputs in modern societies we need only a demand of biosphere capacity to capture $CO_2$ emissions (assuming that energy consumption are only obtained using fossil energy, that will last forever); (ii) one hectare of area dedicated to long-term carbon uptake will be occupied by a virtual global forest capable of growing forever; and (iii) a change of stock in the amount of forest biomass is the only available solution for storing $CO_2$ emissions. We will discuss these assumptions more in detail in Section 5.

## 4. Conceptual problems with the assessment of demand (EF) and supply of non-energy-related biocapacity

### 4.1. The EF accounting protocol has no external referents

As discussed in Section 2, theoretical ecologists base their assessment of the sustainability of human exploitation of natural processes on a comparison of empirical data gathered from The natural density of the flow of interest in unaltered ecosystems ($\Phi_{NAT}$) and The actual density of the flow of interest in the investigated, altered system ($\Phi_{ACT}$).

Hence, these two empirical datasets result from the observation of two distinct sets of *external referents*, that is, *observable attributes* of investigated systems.

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...).

Proper handling of the issue of scale is of particular importance for carrying out a useful analysis of the effect of trade. According to the EF assessing the amount of land embodied in imports and by calculating the net effect of trade (import minus export) one can check whether a specific country imports "ghost land" when importing biomass (food, feed and timber) from other countries. For example, for the import of feed alone the Netherlands uses almost four times more hectares of cropland than those available in the country (van Vuuren et al., 1999, p. 53). However, to find this exact amount of "ghost land" imported by the Netherlands (local assessment) we should use a factor of equivalence referring to local yields. We should either calculate the equivalent land that would be required if the imported feed were produced in the Netherlands (as done by van Vuuren et al., 1999) or we should consider the local yields of the countries producing the imported feed and assess the actual land used for the production of the imported feed within these exporting countries. The assessment of the National Footprint Accounts does neither of this. Instead, it computes virtual global hectares of demand and supply of biocapacity that are located neither in the Netherlands nor in the countries exporting the commodities used by the Dutch (see also Wiedmann and Lenzen, 2007). This choice implies that the resulting numbers do not have an external referent. What is measured in the NFA protocol are densities of virtual flows produced by generic virtual global hectares and determined by "yield factors" and "equivalence factors". The final result is that the NFA protocol can only indicate whether or not the Dutch are using – in average terms – someone else's land for their consumption of food and biomass. But how useful is this information for quantitative analysis or policy advice?

It is well known that trade can facilitate the solution of problems of inhomogeneous spatial distributions of people, resources, capital and environmental capacity (van den Bergh and Verbruggen, 1999). Because of the flow of exports and imports something is gained and something is lost within each one of the trading countries. But can the EF 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? The answer is negative: no insight can be gained in relation to these questions using the EF approach (see also Fiala, 2008). Working with world averages the peculiarity of local situations (heterogeneity among countries) is missed. The Stiglitz commission (CMEPSP, 2009:71), confirming the criticism of van den Bergh and Verbruggen (1999), states:

> *164. The results [of the EF] 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 ecological deficits, whilst sparsely populated (high biocapacity) countries like Finland enjoy surpluses can be seen as part of a normal situation where trade is mutually beneficial, rather than an indicator of non-sustainability.*

Addressing the issue of sustainable development requires us to use simultaneously non-equivalent definitions of costs and benefits on different scales and dimensions, (Giampietro et al., 2006, 2013).

### 4.2. Poor handling of the analysis of ecological services

In relation to this point let us start again from the claims made in the 90s by the proponents of the EF analysis. The EF is "based on a calculation of the aggregate area of land and water in various ecological categories, that is claimed by participants in this economy to produce all the resources they consume and to absorb all the wastes they generate on a continuous basis, using prevailing technology" (Wackernagel and Rees, 1997). How is this claim is supported by the GFN protocol?

In the protocol the accounting only provides information on different levels of alteration of ecosystems, comparing the local system with the global average. None of the two assessments is based on variables capturing the actual situation of ecosystem stress or the quantity or quality of "natural capital" in relation to expected natural states of ecosystems. Indeed, the EF protocol ignores serious ecological and biophysical constraints to the sustainability of economic development, such as:

- The metabolism of water flows within both ecosystems and socio-economic systems. Shortage of water is likely to become one of the most important constraints to economic growth and ecological sustainability in the third millennium.
- Soil health. The health of soil is essential for sustained food production and is a well-recognized crucial factor for sustainability of human development.
- The growing shortage of minerals. Oil is not the only resource peaking in the new millennium. The dramatic increase in the price of metals clearly shows that the world economy is facing shortages of other raw materials. However, minerals are not considered as relevant components of the ecosphere or relevant inputs for socio-economic systems by the EF accounting.
- The increasing disturbance of bio-geochemical cycles, with locally dangerous unbalances between requirement and supply (e.g., nitrogen and phosphorous accumulation generating eutrophication in water bodies). Quite to the contrary, an increase in use of fertilizer is seen as positive for ecosystems in the EF analysis.
- The accumulation of pollutants in the atmosphere, such as endocrine disruptors, persistent organic pollutants, ozone-layer-aggressive chemicals, radioactive wastes, and pesticides, some of which can undergo biological amplification and show non-linear effects difficult to handle in quantitative terms.
- Factors of biological and ecological stress generated by increasing human tinkering with genetic material and unnatural densities of both people and exploited animals. The use of GMO's is

perceived as an improvement by the EF analysis in as far as it leads to increased crop yields (see Section 3).
- The growing threat to the preservation of biodiversity through destruction of natural habitat. As discussed earlier, the destruction of natural habitat for monoculture production is seen as a positive change in the EF accounting.

### 4.3. The "non-energy related" biocapacity of the world always remains constant

As observed by Haberl et al. (2001, p. 39):

> "On the global level, 'overshoot' with respect to grassland or cropland is impossible except for changes in grain or meat storage because it is impossible to harvest more grass or grain than has been growing in the current year. Therefore, on a global level, consumption of these products must be close to production, at least for a 5 or 10-year average".

As discussed in Section 3 same considerations apply to forests, built up land, and fishing areas, so that the only factor accounting for the overshooting is the carbon footprint, e.g. the land area needed to offset $CO_2$ emission from energy production, to which we turn next.

## 5. Conceptual problems with the assessment of the carbon footprint

We now provide a critical appraisal of the assumptions underlying the GFN's assessment of the "fossil-energy-related" demand of biocapacity, the original definition of this component (e.g., Rees and Wackernagel, 1994), now called the carbon footprint. There are three problematic assumptions in the claim made in the GFN protocol that it is possible to express the demand of biocapacity for producing and consuming a given amount of energy carriers in a society in "hectares of virtual land equivalent". As a matter of fact, even when trying to defend the logical foundations of the EF approach Ferguson (1999) has to admit that this is a problematic issue: "*The logic of assessing the 'energy footprint' on the basis of the amount of the ecological space needed to absorb the carbon dioxide emitted by burning fossil fuels is extremely shaky!*" (p. 152). It should be noted that in the latest protocol (last publication in 2013, Borucke et al.) this logic has not been changed.

We illustrate and criticize each of the assumptions used in this logic below (Sections 5.1–5.3).

### 5.1. Assumption 1. Land required for energy: only the sink side is considered

According to the original definition of "biocapacity for energy" proposed by Rees and Wackernagel (1994) the ecological footprint of fossil energy can be calculated in two ways:

> "Energy Land" can be defined in two ways. . . an estimate of the area of average productive land that would be required to produce a flow of high quality biomass energy today (e.g. ethanol) equivalent to the present flow of commercial hydrocarbon energy. . . An alternative estimate of fossil energy land requirement can be obtained by calculating the area of čarbon-sink" forests that would be required to sequester the $CO_2$ emissions released by contemporary hydrocarbon combustion.

Correspondingly, in the earlier versions of the EF protocol the idea was to consider a fully renewable, zero emission energy system based on biomass (e.g., biofuel). This would allow for the assessment of a given area in which the sink (uptake of $CO_2$) and supply (energy input in the form of biofuel) functions coincide. As explained by Wakernagel et al. (1999):

> "For fossil gas, liquid fossil fuel and solid fossil fuel, we estimate 1 ha of footprint for the annual consumption of 93, 71 and 55 GJ, respectively. This is calculated by assessing the land requirements for the corresponding $CO_2$ absorption, using data from the Intergovernmental Panel on Climate Change (1997). Slightly larger footprints would result if the fossil fuel footprint was calculated with the land areas necessary for growing biochemical substitutes" (Wakernagel et al., 1999, p. 382, emphasis added).

Thus, given that the requirement of land for the sink and for the supply side are assumed to be similar, Wackernagel et al. (1999) decided to focus only on the sink side (absorption of $CO_2$). Unfortunately, this cannot be justified. As discussed in detail in Giampietro and Mayumi (2009), the supply-side conversion factor of 71 GJ/ha/year (for liquid fossil fuel) assumes a sustainable net production of liquid biofuel of about 71 GJ/ha/year (0.22 W/m$^2$). This level is not even reached by the gross production of ethanol in the USA (66 GJ/ha/year in 2005), notwithstanding the heavy inputs of fossil energy. In a fully renewable system of agro-biofuel production (no fossil energy inputs) the internal consumption of energy carriers to make energy carriers would imply a non-linear increase in the land demand per unit of net energy carrier supplied. Consequently, the land required for the supply of energy carrier to society would be 10 times more than the conversion factor used in the earlier EF protocols. Moreover, the internal loop of consumption of energy carriers in this production technology implies a concurrent consumption of various other production factors, such as labor, technology, water, and soil. Given existing benchmarks a significant production of energy carriers based on a fully renewable biofuel system is simply not an option (Giampietro and Mayumi, 2009). In conclusion, it is impossible to assume that the requirement of biocapacity for absorbing $CO_2$ (the sink side of the metabolic process) also captures the requirement of biocapacity on the supply side. In practice, the EF assessment ignores the space required for producing the energy input consumed by society. The new GFN protocol has dropped the assessment of the supply side altogether. The protocol apparently assumes that: (i) the only primary energy source used in modern society is (and will remain in the future) fossil energy; and (ii) the only concern of biocapacity for energy is how to avoid $CO_2$ accumulation in the atmosphere. There is a logical incoherence here. Using fossil energy is about depleting stocks, nevertheless the supply of fossil energy (a non-renewable resource) is assumed to be unlimited in the future by default. The Hicksian/sustainable concept of living on the 'interest' of natural capital has been abandoned in the practice of the EF computation.

### 5.2. Assumption 2. Dimensional coherence in the proposed equation of equivalence is overlooked

The recently proposed protocol for assessing the carbon footprint is based on the calculation of an area capable of providing the required sink capacity for a steady-state flow of $CO_2$ production. Hence, when calculating the carbon footprint the EF protocol first has to translate the given flow of energy carriers consumed in a country into a given flow of $CO_2$ emission. In a second step the steady-state flow of carbon is then converted into an area equivalent. While the first step is already problematic as discussed above, the second presents us with an serious incoherence. The approach establishes a quantitative equivalence between a *flow* measured in tonnes 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 capable of fixing a certain amount of carbon – corresponding to the official SI dimension of kg/m$^2$. This procedure violates the elementary logic of accounting, as well as the formal matching of dimensions in the resulting quantitative expression, i.e. the EF uses an identity in which the terms on the right and left of the equal sign are measured in different units. Apart from this, a hectare of forest cannot grow (and fix $CO_2$) forever.

> "... only 'young' forests fix significant amounts of carbon, and they do so at a rate quite significantly below net primary production (NPP), because a considerable proportion of the yearly productivity in forests is oxydized again each year and does not contribute to an increase in carbon stocks in the ecosystem. Moreover, maturing forests only sequester significant amounts of carbon for some decades, after which their net carbon balance gets close to zero as they approach a climax state. Therefore, fossil-energy land cannot be used again and again each year; instead, as carbon fixation goes down in maturing forests new land would have to be acquired for carbon sequestration (and mature forests would have to be left standing)." Haberl et al. (2001, p.30).

Using an analogy with water flows, the proposed approach wants to assess the size of a bucket (measuring its bottom area) needed to contain the water coming out continuously from a faucet at a determined rate (e.g., 100 l per hour). The containment of water given by the bucket can only be temporary. Sooner or later, the bucket will be full. After reaching that point additional buckets will be needed in order to absorb the relentless flow of water. The final space needed will be infinitely increasing as the steady state involves the continuous addition of new buckets in addition to the space needed to store the full ones.

In the same way, the hectares of virtual land serving as carbon sink will sooner or later become a virtual mature forest in climax state that can no longer absorb $CO_2$. New hectares of young virtual forests will be needed to absorb the continuous emission of $CO_2$ generated by society. The present discussion makes it clear how the present EF protocol is totally dependent on a very problematic assumption. A global sensitivity analysis (Saltelli et al., 2012) would easily identify this assumption as critical and the resulting inference volatile. Thus the GFN protocol analysis generates numbers with a worrying 'pedigree', in the sense of van der Sluijs et al. (2005).

### 5.3. Assumption 3. The EF simplification relies on a series of flat conversion factors

It is impossible to represent the energetic metabolic pattern of a modern society using only a single numeraire for accounting energy (Giampietro et al., 2013; Giampietro and Sorman, 2012). Depending on the mix of primary energy sources (how the energy carriers are produced) and the mix of energy carriers (electricity and thermal energy) used in society we can have a different relation between the gross energy requirement (an assessment usually measured in Tons of Oil Equivalent), the final energy used by society, and the corresponding $CO_2$ emissions (Giampietro et al., 2013). Moreover Tons of Oil Equivalent do not map onto actual quantities of $CO_2$. Therefore, there is no direct relation between the Carbon Footprint and the energy used by society.

Furthermore, the EF 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).

Thus in the present formulation the EF analysis is inadequate to explore the universe of possible adjustments in life style (mix of consumption), in mix of land uses (through a wise use of trade and specialization), and/or in mix of technologies. The rigid definition of "prevailing technology" does not allow the EF 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).

## 6. Conclusions

### 6.1. The lesson to be learned for integrated assessment for sustainability

The EF approach cannot handle the complexity of sustainability because of its goal to deliver a simple narrative (a single number addressing all dimensions of sustainability).

In the Stiglitz report – in a section aptly entitled '*Uncertainty is also normative*' one reads (CMEPSP, 2009:75)

> 184. In addition to raising technological issues, measuring sustainability with a single index number would confront us with severe normative questions. The point is that there can be as many indices of sustainability as there are normative definitions of what we want to sustain.

Among statisticians the aggregation of multidimensional phenomena to single indices is seen as problematic. Again citing the Stiglitz report (CMEPSP, 2009:65) '[in relation to aggregate measures] *normative implications are seldom made explicit or justified*'. We believe this remarks also holds for the EF.

Neither dollars (e.g., the World Bank's Natural Capital) nor hectares (the Ecological Footprint) are neutral enough to be useful for compressing into a single number a wealth of indicators that do not always fit neatly into the chosen metaphor (e.g., using 'hectares' to account for the fragmentation of landscapes, or subtracting 'dollars' from the GDP to correct for gender inequality).

A quality assessment should be provided via sensitivity analysis (Saltelli et al., 2012; Saisana et al., 2005; Paruolo et al., 2013), which EF cannot easily afford. Any sensitivity analysis would reveal the volatility of the inference, thereby making the EF vulnerable to the critique of Pseudo-Science as defined by Funtowicz and Ravetz (1990, 1994) when discussing quality criteria for science used in support to policy: "[pseudo-science is] where uncertainties in inputs must be suppressed lest outputs become indeterminate." Saltelli et al. (2013) and Saltelli and Funtowicz (2013), extending the work of van der Sluijs et al. (2005), have proposed a checklist for quality of a modelling process. The EF would fail such a checklist for match between complexity and accuracy, defensibility of the assumptions, and transparency of the construct.

As mentioned in the introduction some of the points raised in the present work are treated in a paper recently published on PLOS biology (Blomqvist et al., 2013a,b), including e.g. the fact that if one omits $CO_2$ emission the planet seems for the rest to be on a sustainable path according to the EF, the total volatility of the numbers produced by the EF due to the uncertainty on carbon sequestration rate in forest, as well the paradoxical policies which the EF accounting would imply. The reaction of Rees and Wackernagel (2013) states that:

> 'However, there is nothing gained by not knowing one's country's biocapacity balance, and there are presently no better estimates than those delivered by Global Footprint Network's current Footprint accounts.'

From this claim it is evident the concept of biocapacity defined by the EF proponents is a misleading concept pointing toward wrong policies, and blind to the majority of ecological high concern issues as discussed both here and elsewhere. One does not understand then what is gained having the 'best estimate' of this number – the EF biocapacity calculated in virtual global hectares using a logically challenging protocol – while one understands very well today the implications of having policies driven by a wrong metric.

Thus the EF can make it to the headlines claiming that "August 22 was Earth Overshoot Day. In 8 Months, Humanity Exhausted Earth's Budget for the Year" without mentioning problematic assumptions and methodological inconsistencies. The spurious accuracy of August 22 (as distinct from August 21 or 23) gives the 'viewers' a false sense of security about how accurately the experts can measure the damage and to reassure that after all we are only one third away from sustainability.

The EF gives comfortably low estimates of the level of overexploitation of natural resources. In fact, a sound biophysical analysis of ecological constraints would show a grimmer reality. As illustrated in the examples of quantitative analysis given in Giampietro and Pimentel (1991) ecological theory forces upon us the realization that there is no chance that the pattern of production and consumption of goods and services typical of developed countries might be expanded all over the planet for a population of 9/10 billions. Any serious ecological analysis of the sustainability of current trends would entail the immediate dismissal of the fairy tale of perpetual growth through technical progress (more efficiency) and globalization (more market).

In relation to this point, how useful is the quantitative indication given by the EF protocol that our civilization is overshooting the carrying capacity of our planet by 50%? When comparing the amount of nitrogen contained in synthetic fertilizer used in world agriculture – 100 million tonnes/year (Wackernagel et al., 1999) – with the amount of nitrogen made available to the plants by natural cycles – 60 million tonnes/year (MEA, 2005) – we see that the total flow of nitrogen input used for the gross primary productivity on this planet – 160 million tonnes/year – represents the flow of nitrogen that would be fixed by 2.66 planet Earths operating in purely ecological conditions. This is to say that when considering only the existing production of food (just one of the six land categories considered by the EF protocol), the demand of biocapacity that would be required to get the flow of nitrogen only is much more "unnatural" than the 50% difference with natural levels of productivity computed by the EF.

### *6.2. The lesson to be learned for science for governance*

The EF has been enthusiastically embraced by the media at face value, as its narrative corresponds to humans' fear and intuition. The academic community working in the field of sustainability science could have done more to criticize the EF shortcomings.

While the layperson cannot be blamed for the former element, the EF developers and the scientific community should bear responsibility for the latter. As mentioned in the introduction the extraordinary success enjoyed by the Ecological Footprint protocol is due to the relative simplicity of the message coupled to a substantially harmless policy prescription. The EF 'proves' that humankind is overshooting the ecological carrying capacity, but not dramatically, thus pleasing both sides of the ecological debate on the limits of growth.

A different paper should address how it was possible for the Ecological Footprint to survive the criticism it received and continues to receive, while enjoying both media support and take up by relevant actors such as the World Wildlife Fund, the United Nations Environment Program, the United Nations Development Program, the International Union for Conservation of Nature, and the Convention on Biological Diversity (Blomqvist et al., 2013a). Based on our experience this success is due to a differentiated communication strategy by EF proponents. When talking to a general audience the key claim is that the EF is science-based. When engaging with critical practitioners the claims are that the EF is being continuously improved, and that that the world is a better place with the EF than it would be without it.

### *6.3. The way forward*

Complex adaptive systems can only be perceived and represented using simultaneously different narratives and different models for quantitative assessment across dimensions and scales (Giampietro, 2003; Giampietro and Mayumi, 2004; Giampietro et al., 2006, 2014). These different quantitative assessments are not equivalent (neither logically nor formally coherent) and cannot be aggregated together in a single index. This entails that we can use ecological theory to individuate and measure the existence of different biophysical constraints associated with the need of preserving the integrity of ecological processes. However, these constraints can only be defined one at the time (e.g., for energy security, food security, water security, biodiversity protection) at different scales while using non-equivalent descriptive domains, as done for example in terms of "Planetary Boundaries" (Rockström et al., 2009), where each proposed characterization refers to different sustainability issues (in relation to both the supply and the sink side). In conclusion a systemic biophysical analysis of ecological constraints relevant for policy discussion of sustainable development would require the development of a multi-level multi-scale integrated analysis capable of delivering "a logical and complete system of multiple, complementary indicators, based on a systems perspective of interconnected environmental problems" (van den Bergh and Verbruggen, 1999, p. 64).

### *Disclaimer*

The ideas here contained in the present article are those of the Authors and do not represent the views of the European Commission.


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