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Exploring ecosystem services assessment through Ecological Footprint accounting

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A B S T R A C T

Ecosystem services are the benefits that humans derive from Nature. In the last decades, research efforts have been made to better understand the connections between the natural sphere and the human sphere as well as to propose novel approaches to measure the value of ecosystem services. While economic valuation has so far been the most commonly used approach – expressing ecosystem services' value in monetary units – recent efforts have focused on alternative qualitative or biophysical accounting approaches to express the value of ecosystem service in physical units.

The role of Ecological Footprint accounting as a biophysical approach for measuring the value of ecosystem services through a surface-equivalent unit is here investigated. This accounting tool allows keeping track of both the human demand on, and the Nature's supply of, a precise sub-set of ecosystem services thus being able to make an ecological balance at the country level. A comparison between Ecological Footprint and economic valuation analyses is finally performed, for the forest ecosystem type, to highlight complementarities and correlations of these different approaches.

Contents

1. Introduction

Ecosystem services are Nature's benefits to people. These include provisioning services such as food and fresh water; regulating services such as climate control; supporting services such as soil formation and photosynthesis; and cultural services such as recreation, spiritual and educational values (Costanza et al., 1997; MEA, 2005; TEEB, 2010). Interest in the understanding, modelling, valuation and management of ecosystem services has grown rapidly in the sustainability debate since 2005, when it gained broader attention following the publication of the United Nations' Millennium Ecosystem Assessment (MEA, 2005; Braat and de Groot, 2012; Costanza and Kubiszewski, 2012). Since then, a few international initiatives have been undertaken for assessing the connection between Nature and the human society and economy,

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Table 1
Overview of key quantitative biophysical accounting methods for the assessment of Ecosystem Services.

Method name	ESs accounted	Description	References
Change in stock/ quantities	P	Increasing/decreasing quantities of an ecosystem good indicate increasing/decreasing values	Remme et al., (2014)
Ecological integrity	All	The higher the ecological integrity (defined as the basic requirements for the stability of biotic communities), the higher the value of that ecosystem for that service	Johnston et al., (2011)
Biodiversity indexes	All	The higher the biodiversity (measured through indexes such as the Living Planet Index or the Red List Index), the higher the service value of that ecosystem	Obrist and Duelli, (2010)
Ecological Footprint	P, R	The area and productivity of ecosystems within a territory (i.e. the biocapacity) used as proxies for the ecosystem service value of that territory	Galli et al. (2014), Galli et al. (2012) This study
Changes in efficiency	P, R	The more efficient an ecosystem is in producing goods and services (in terms of resource use per service unit), the higher its value	McCarthy et al., (2011)
Emergy	All	The more equivalent solar energy is embodied in the ecosystem components, the higher is the ecosystem service value	Coscieme et al., (2014)
Eco-exergy	All	The higher the level of genetic information and biomass in the ecosystem, the higher the ecosystem service values	Jørgensen, (2010)

Note: letters P and R reported in the second column refers to "provisioning" and "regulating" ecosystem services, respectively, while "all" refers to the whole set of ecosystem services according to the CICES classification (see Haines-Young and Potschin, 2013).

including the Economics of Ecosystems and Biodiversity (TEEB, 2010), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES – see Díaz et al., 2015), the System of Environmental-Economic Accounting (SEEA – UN et al., 2014a,b) and the Common International Classification of Ecosystem Services (CICES – Haines-Young and Potschin, 2013).

Ecosystem functions and biodiversity constitute the natural capital stock that yields the ecosystem service flows into the future (Costanza and Daly, 1992). However, ecosystems cannot provide any benefit to people without the presence of people (human capital), their communities (social capital), and their built environment (built capital) (Costanza et al., 2014a). Humanity depends on the biosphere for its well-being and a relational order exists between the different forms of capital, with built and human capital embodied into social capital, and social capital embodied, in turn, into natural capital (Wackernagel et al., 2002; Pulselli et al., 2015).

Two main approaches exist to understand and measure the value of ecosystem services: 1) a monetary valuation approach, requiring that ecosystem services are assessed in monetary units; 2) a biophysical accounting approach, based on quantitative empirical measurements.

Monetary valuation is the most developed approach to assess the value of ecosystem services. It constitutes a way to include the value of ecosystems and biodiversity in cost-benefit analyses and allows including the costs of environmental degradation in macroeconomic "beyond-GDP" type of indicators (Costanza et al., 1997; Costanza et al., 2014a,b). As such, the economic assessment of the value of ecosystem services represents an effective way to communicate to policymakers, the business sector (Hanson et al., 2012), and the general public the importance of environmental conservation (TEEB, 2010). Through environmental economics methods, which aim at weighting in monetary terms the use and non-use values of ecosystem services, it is possible to track a wide basket of ecosystem services, although these evaluations often depend on the variability of market prices as well as individual preferences (De Groot et al., 2012; Christie et al., 2012).

Given the complexity of Nature and the high degree of approximation of the economic-based approach, a few scientists and researchers have recently suggested (e.g., Costanza et al., 2014a) that research efforts should be focused on alternative analyses based on more spatially explicit and dynamic methods, to capture the intrinsic value of natural capital and its capacity to deliver goods and services to humans. Such an alternative to monetary valuation is envisaged by qualitative and biophysical accounting methods aiming at expressing the value of ecosystem services in other than monetary units (i.e. land, energy, productivity, etc.) (e.g. Burkhard et al., 2012; Burkhard and Maes, 2017).

Accordingly, the aim of this paper is to analyze such an alternative, biophysically-based, approach for the assessment of ecosystem services. Specifically, we discuss here the possibility of using Ecological Footprint accounting as a biophysical measure for the assessment of ecosystem services. A comparison between the results obtained from economic valuations and those obtained from the Ecological Footprint assessment is also provided to highlight advantages and limitations of both methods.

2. The biophysical evaluation of ecosystem services: Ecological Footprint accounting

The ability of biophysically-based methodologies such as LCA (Koellner and Geyer, 2013; Othoniel et al., 2016), Emergy analysis (Coscieme et al., 2014; Pulselli et al., 2011, 2015), Water Footprint (Vanham, 2016), biodiversity assessments (Schneiders et al., 2012), as well as accountings of economic (Costanza et al., 1997; Fisher et al., 2008) and other human-derived forms of capital (Jones et al., 2016) to track ecosystem services has been widely investigated in the last decades. Such methodologies can be either qualitative or quantitative (see Table 1 for an overview of existing approaches).

Qualitative approaches are mainly based on descriptive assessment of ecosystem services provision at a certain spatial scale without any actual measurement or quantification, such as descriptive tables and color-coded maps illustrating the potential of particular areas to provide ecosystem services (see Burkhard et al., 2009). Conversely, proper biophysical accounting methods include the use of physical units to quantify the flows of ecosystem services from the environment to human socio-economic systems (i.e. raw materials and resources) or even quantify the capacity of ecosystems to provide goods and services (UN et al., 2014a). The value of grassland for milk production, for instance, can be expressed in tons of milk per year rather than using the market value of that same amount of milk. The chosen unit of measure largely depends on the objective of the evaluation as well as on users' considerations about the most effective way to communicate results to a specific audience, in a given context.

One of the major drawbacks of biophysical evaluations is represented by the fact that a common physical unit of measure is hardly associable to the different kinds of services. In other words, these methods often fail in aggregating different multiple services from an ecosystem, thus being unable to provide an overall estimate of that ecosystem's value or the overall values of multiple ecosystems within a given geographical or geopolitical territorial unit. Recognizing such drawback prompted us to investigate whether Ecological Footprint accounting can overcome the above limitation and be used as a composite biophysical measure of ecosystem services.

Ecological Footprint Accounting (Wackernagel et al., 2002) is an environmental accounting tool able to convert nature's contribution to human well-being in a common, surface-equivalent unit of measure: the global hectare (Galli et al., 2007; Galli, 2015). This tool is able to quantify and aggregate both the human consumption of ecosystem services and their supply from the Biosphere into an overall estimate of ecosystems value that otherwise, in most biophysical accounting methods, would be quantified independently (Galli et al., 2014). As such, the Ecological Footprint is a systemic environmental accounting tool possibly able to provide a first quantitative biophysical assessment of ecosystem services by means of two metrics:

- On the demand side, the *Ecological Footprint* measures the biologically productive land and sea area – also called ecological assets – needed to produce a specific sub-set of provisioning and regulating services that a population uses (see Section 3 for a definition of this sub-set).
- On the supply side, *biocapacity* tracks the ecological assets available in countries, regions or at the global level and their capacity to produce such ecosystem services.

A country's Ecological Footprint of consumption (EF_C) is derived by tracking the ecological assets demanded to produce the provisioning and regulating services "harvested" within the geographical boundaries of such country (EF_P), plus those imported (EF_I) and minus those exported (see Borucke et al., 2013). For any ecosystem service *i* appropriated by humans, irrespective of whether it is locally produced, imported or exported, the EF is calculated by means of the below general equation (further details on the specific equations to account for the various ecosystem services is provided in the Supplementary Material, Annex A):

$$\mathrm{EF} = \frac{P_i}{Y_{W,i}} \cdot EQF_i \tag{1}$$

where P is the amount of any service *i* (a primary resource such as food or fiber or an out-flowing waste such as carbon dioxide for which sequestration is needed) that is appropriated by humans; $Y_{W,i}$ is the annual world-average yield for the production of the service *i* (or its carbon uptake capacity in cases of out-flowing CO_2 emissions); and EQF_i is the equivalence factor for the type of ecosystem (e.g., a crop, a forest, etc) producing the service *i* (see Supplementary Material, Annex A).

On the supply side, biocapacity (BC) represents a quantitative assessment of the actual annual ecosystem service budget available (i.e., an ecological benchmark) and quantifies nature's ability (due to current management practices) to provide for humans' needs. Biocapacity is calculated as in Eq. (2) and, for each country, it provides an assessment of that country ecological assets' capacity to produce a specific sub-set of resource provisioning and regulating services (see Section 3 for a description of this sub-set).

$$\mathrm{BC} = \sum_i A_{N,i} \cdot YF_{N,i} \cdot EQF_i \tag{2}$$

where $A_{N,i}$ is the bioproductive surface of an ecosystem – the ecological assets – that is available for the production of each service *i* at the country level, $YF_{N,i}$ is the country-specific yield factor for the asset producing such service *i*, and EQF_i is the equivalence factor for the asset producing the service *i*.

Having the same unit of measurement (i.e., global hectares), Ecological Footprint and biocapacity values can be compared to derive an "ecological balance" between the Biosphere's supply of, and humans demand for, ecosystem services. This balance represents one of the main outputs of the system of National Footprint Accounts (NFA), which tracks and compares historical trends of Ecological Footprint and biocapacity for more than 200 countries (GFN, 2017)[1]: when the ecological balance is positive (EF < BC), the country analyzed runs an ecological remainder or surplus; conversely, when the balance is negative (EF > BC) the country runs an ecological deficit.

These accounts are descriptive rather than predictive as they show what such balance "is" and "has been" rather than what it "will be" (Borucke et al., 2013). As such, the Footprint methodology (through its two metrics) is able to quantify the pressure posed on ecosystems by the various human activities (e.g., logging at a rate higher than forest biomass regeneration) but it does not quantify the consequences of such pressure (e.g., forest loss). Within Ecological Footprint analyses, the result of over logging in a year (i.e., deforestation) will be thus detected in assessments through time, as a reduction in forest biocapacity in the following years (see Mancini et al., 2017; Goldfinger et al., 2014).

Although EF and BC are flow measures – meaning that they account for human demand on, and biosphere supply of, annual flows of ecosystem services – they are measured in terms of the underlying ecological assets (i.e., the physical surface of ecosystem types with biotic and abiotic components functioning together) needed to produce these flows (Mancini et al., 2017). Such an approach using sources (the underlying producing assets) and resources (the resulting produced ecosystem services) is similar – in its rationale – to that of the UN SEEA (UN et al., 2014b) in which flows of ecosystem services generated by the ecological assets can be both inputs from the environment to the economy (i.e. forest timber, fishes or crops) and outputs of residues from human activity to the environment (i.e. wastes and emissions).

Specifically, Ecological Footprint accounts for those ecosystem assets where the photosynthetic activity takes place and solar energy is captured by autotrophic organism to structure matter into any form of biomass that humans find useful. These ecological assets, or land types are: i) cropland for food, animal feed, fiber, oil and rubber; ii) grazing land for animal based products (such as meat, milk, dairy products, wool and hide); iii) fishing ground (marine and inland) for fish products; and iv) forests for wood timber products, as well as for sequestration of the carbon dioxide primarily from fossil fuel burning. Built-up surface for shelter and other urban infrastructure is also tracked: by paving over productive ecological assets (e.g., a crop being replaced by an urban area), humans are indirectly and indefinitely appropriating the yearly flows of ecosystem services that such assets would have otherwise provided.

Furthermore, considering that ecosystems provide a number of services simultaneously, Ecological Footprint tracks the various uses of nature by assuming a mutually exclusive function useful to human in each productive surface. This avoids double counting although it results in an underestimation of the actual human pressure in terms of ecological asset appropriation (Borucke et al., 2013; Galli, 2015).

[1] Interested readers are welcomed to review Galli et al., (2014), Weinzettel et al., (2014) and WWF et al. (2016) for further details on global and country-level Ecological Footprint assessments. NFA values for 2013 – the most recent year for which results are available – can be freely accessed at: http://data.footprintnetwork.org/.I.

3. Ecological Footprint and ecosystem services: establishing the relationships

One of the most complete views on the ecosystem services and their connection with the human sphere is provided by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) through its Conceptual Framework (Díaz et al., 2015). IPBES represents a great participatory and consultative process among member countries of the United Nations to strengthen the science-policy interface; it does so by developing assessments of the state of biodiversity and the sustainable use of ecosystem services at sub-regional, regional and global levels. The IPBES Conceptual Framework is the result of such process and provides an overview of the complex interactions between the natural world and the human society. It focuses on key elements such as nature, benefits that people derive from it and people's quality of life. It also highlights the central role that institutions, governance and decision-making bodies play on the links among these elements (Díaz et al., 2015).

In 2016, the Ecological Footprint has been included in the list of IPBES Core Indicators as an indicator of direct (anthropogenic) drivers of change in the state of biodiversity and ecosystems functioning (and their derived services) that affect the supply of nature's benefit to people. The Ecological Footprint tracks such anthropogenic drivers of changes by looking at the final users placing demand on the various economic sectors' outputs. Such outputs, in turn, require resources and ecosystem services to be produced and the Footprint methodology tracks the bio-productive surfaces (i.e. ecological assets) required to produce such resources and ecosystem services. This means that Footprint results do not usually show which economic activities are demanded but rather the consequences, in terms of land appropriation, of demanding the outputs of such economic activities. Recent, input–output based Footprint analyses allow also obtaining Footprint results by consumption/economic activities; examples of these two different ways to break down Footprint results can be found in Galli et al., (2017) and Baabou et al., (2017). Understanding the linkages and interactions between biodiversity, the drivers of biodiversity loss and the Ecological Footprint is thus important to act upon it with the goal of slowing and reversing the ongoing loss of natural habitats and biodiversity (Galli et al., 2014).

Specifically, Ecological Footprint Accounting is able to keep track of a precise sub-set of ecosystem services, such as the provision of biomass-based resources like food, fibers and renewable raw materials (e.g., wood-fuels and plant oils) and the regulation and maintenance of a stable climate through long-term storage of carbon dioxide through photosynthesis. Anthropogenic carbon dioxide emissions represent the only waste that National Footprint Accounts currently track, as they can be easily converted into the biologically productive area necessary to absorb them (Kitzes and Wackernagel, 2009; Mancini et al., 2016). Other regulating services such as air quality regulation, moderation of extreme events, biological control, erosion prevention and maintenance of soil fertility as well as cultural ecosystem services such as recreation, aesthetic appreciation and inspiration are not captured by the Ecological Footprint as a method to refer such services to a specific bioproductive (photosynthetic) surface has not yet been identified nor investigated (Kitzes et al., 2009).

In recent years, several efforts have been made to define a common classification of ecosystem services (e.g. MEA, 2005; TEEB, 2010; Pascual et al., 2017), as a first step towards a possible standardization/integration of different approaches for ecosystem service assessments. For the purpose of this paper, we followed the ecosystem services classification provided by the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2013) and Table 2 reports the subset of ecosystem services taken into account by the Ecological Footprint methodology (as currently implemented) vs. those the method is currently unable to track.

4. Monetary valuation vs. Ecological Footprint assessment of ecosystem services: The case of forest ecosystems

To assess the relevance of the Ecological Footprint as a biophysical accounting tool for ecosystem services assessment, Footprint and monetary valuation data for approximately 200 world countries were collected and compared.

While the Ecological Footprint method is able to solely capture a few ecosystem services (as reported in Table 2), the monetary valuation can theoretically keep track of Nature's supply of a wider range of ecosystem services, as proved by De Groot et al. (2012) and Costanza et al. (1997, Costanza et al. (2014a)); as such, for properly comparing the two approaches, data solely related to provisioning and regulating services occurring in forests – i.e., raw materials and climate regulation data for the monetary valuation, and forest land and carbon Footprint data for the Footprint assessment – were selected and used in the comparison (see Table 1S in Annex B of the Supplementary Material).

Ecological Footprint data was drawn from the National Footprint Accounts 2017 Edition (GFN, 2017) database and refers to the year 2013, the last year for which data is available. Per capita Ecological Footprint of both consumption and production for the forest and carbon Footprint components ($EF_{forest+carbon}$), per capita forest BC values (BC_{forest}) as well as per capita ecological balances for the forest ecosystem (i.e. the difference between $EF_{forest+carbon}$ and BC_{forest}) were considered (see Supplementary Material, Annex A for further details on these parameters). For the monetary valuation (ES), given the lack of country-specific estimates, the economic value of the services potentially supplied by a world average hectare of forest (expressed in 2007 US\$ ha^{-1} yr^{-1}) drawn from Costanza et al. (2014a) was first adjusted to the year 2013 on the basis of inflation and consumer price index data[2] and then scaled to the total forest coverage in each country in 2013 to get an estimate of the economic value of countries' ecosystem services from forests in 2013. Results were then divided by each country's 2013 population data to express results in 2013 US$ per person per year. For consistency with the Footprint assessment, the economic value of the services provided by a world average hectare of forest was calculated by solely adding up the service value of climate regulation and that of raw material provision (ES_{RM+CR}). It should be noted that the use of country-specific valuation data could further improve this analysis as, for instance, the value of climate regulation provided by tropical forests is higher than that of temperate or boreal forests (Costanza et al., 2014a).

Two pair-wise comparisons were performed – ES_{RM+CR} vs. consumption $EF_{forest+carbon}$ and ES_{RM+CR} vs. BC_{forest} – to investigate whether a correlation exists between monetary valuations and either the supply or the demand side of the Footprint methodology. As reported in Fig. 1, results show no statistical correlation between the forest Ecological Footprint parameter and economic value data for the forest ecosystems (Pearson correlation 0.05), while a strong correlation was found between forest Biocapacity and economic value (0.95). We interpret these results as an indication that biocapacity can be considered a proper biophysical proxy measure for the supply of ecosystem services, given its high correlation with the economic valuation data provided by Costanza et al. (2014a). Conversely, being a measure of human demand rather

[2] This conversion is performed through the CPI Inflation Calculator provided by the US Bureau of Labour Statistics and available at https://data.bls.gov/cgi-bin/cpicalc.pl.T.

Table 2
Ecological Footprint's coverage of the CICES-defined Sections and Classes of Ecosystem Services (CICES classification available at: https://cices.eu/).

	Ecosystem services directly measured by the Ecological Footprint Methodology	Ecosystem services indirectly/partially measured by the Ecological Footprint Methodology	Ecosystem services not accounted for by the Ecological Footprint Methodology
Provisioning Services:	- Cultivated crops - Reared animals and their outputs - Fibers and other materials from plants, algae and animals for direct use or processing - Materials from plants, algae and animals for agricultural use - Plant- and animal-based resources - Plant- and animal-based energy sources	- Surface/ground water for drinking/non-drinking purposes NOTE: the Ecological Footprint method is not able to directly track the role of ecosystems in the global hydrological cycle; however, the presence or absence of freshwater affects the productivity of crops, plants and trees, which in turn affects the biocapacity of countries A direct consumption-based indicator of freshwater use is the Water Footprint (see Hoekstra et al., 2011 for detailed description)	- Genetic materials from all biota
Regulation and Maintenance Services:	- Global climate regulation by reduction of greenhouse gas concentrations	- Pollination and seed dispersal NOTE: the method is not able to directly track the role of pollinators; however, the presence or absence of pollinators affects the productivity of plants and trees, which in turn affects the biocapacity of countries	- Micro and regional climate regulation - Flood protection - Storm protection - Bio-remediation by micro-organisms, algae, plants, and animals - Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals - Buffering and attenuation of mass flows - Mass stabilization and control of erosion rates - Pest/Disease Control - Maintaining nursery populations and habitats NOTE: The method does not track the capacity of ecosystems to provide habitats for species. However, the Ecological Footprint of production vs. biocapacity comparison provides a measure of the pressure humans place on ecosystems and the biodiversity that inhabits them, which potentially constitutes a proxy for habitat disruption/loss (see also Galli et al., 2014)
Cultural Services		- Experiential use of plants, animals and land-/seascapes in different environmental settings NOTE: Although not directly accounted, tourism activities can be extrapolated using Ecological Footprint methodology since resources consumed and waste produced by tourists are accounted and allocated on local population. For further details, see Patterson et al., 2007, Patterson et al., 2008	- Scientific - Educational - Heritage, cultural - Entertainment - Aesthetic - Symbolic - Sacred and/or religious - Existence - Bequest

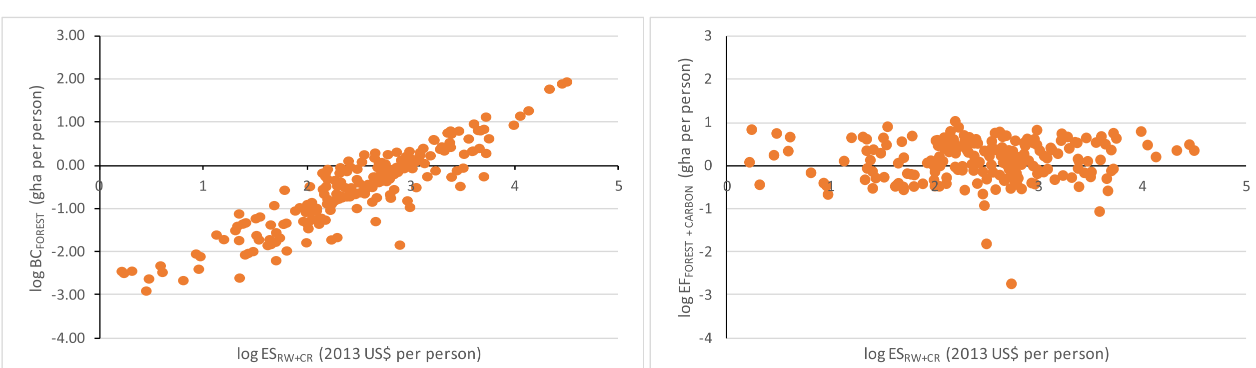

Fig. 1. Regression plots of per capita economic value of forest's raw material provision and climate regulation services of world countries (log ES_{RM+CR}) as a function of per capita forest biocapacity (log BC_{FOREST} – left panel) and per capita forest plus carbon components of the Ecological Footprint of consumption (log $EF_{FOREST + CARBON}$ – right panel).

than nature supply, it is not surprising that the Ecological Footprint does not correlate with the economic valuation nor with the biocapacity values (see also Patrizi et al., 2010; Weinzettel et al., 2013). Nevertheless, the added value of the Footprint methodology – on which future research could leverage – resides in its ability to compare human demand with ecosystems' supply of the considered services, thus providing an *ecological balance* of the human-environment relationship that would otherwise not be possible with sole economic valuations (as they usually only provide an assessment of the ecosystem services' supply).

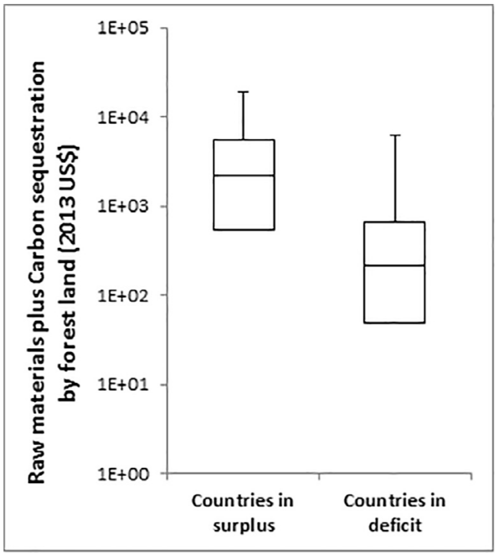

Fig. 2. Distribution of the 2013 forest ecosystem service value (in 2013 US$) of Raw Materials plus Carbon Sequestration in countries in with $BC_{forest} > EF_{forest+carbon}$ (n = 50) and $EF_{forest+carbon} > BC_{forest}$ (n = 169).

Moreover, in comparing countries' ecological balances for the forest and carbon Footprint components with monetary valuations, weak correlation (0.10) was observed for countries that run an ecological deficit (i.e. $EF_{forest+carbon} > BC_{forest}$), whereas a strong correlation (0.96) was found for countries running an ecological surplus (i.e. $BC_{forest} > EF_{forest+carbon}$). This is in line with the fact that the ecological deficit corresponds to the highest share of Ecological Footprint, whereas the ecological surplus depends on the highest biocapacity share, reflecting in turn a greater capacity to supply ecosystem services. As such, the biocapacity term of Footprint assessment is directly correlated with the economic valuation of services' supply and could be used as a complementary biophysical measurement of the supply of ecosystem services.

A box plot analysis of the results (Fig. 2) also shows that countries characterized by a surplus in forest biocapacity have an average economic value for ecosystem services that is an order of magnitude (10^3 2013 US$) higher than countries running ecological deficits (10^2 2013 US$) in forest.

Finally, Ecological Footprint values have been analyzed by comparing both the EF of consumption (EF_C) and the EF of production (EF_P) for the forest plus the carbon Footprint component with the Biocapacity of countries for forest ecosystems (BC). On the basis of such analysis, four cases were distinguished (Fig. 3; see also Table 1S):

1. $EF_C < BC$ and $EF_P < BC$: this is the case of countries such as Brazil, Bolivia, Paraguay and Congo in which the supply of forest services is higher than their residents' demand for such services, thus being able to satisfy the demand from both national and foreign consumers without exploiting national forests. However, this result should be taken with caution as illegal logging could be taking place thus hiding possible forest overuse and deforestation (Lazarus et al., 2015).
2. $EF_C > BC$ but $EF_P < BC$: this is the case of countries such as Honduras, Montenegro, Senegal and Nicaragua, where the local biocapacity supply seems to be preserved, as the consumption of services from forests is met through imports. This result is consistent with findings from Weinzettel et al., (2013) indicating that countries with a high per capita biocapacity tend to spare more land for nature.
3. $EF_C < BC$ but $EF_P > BC$: a few countries (e.g., Finland, Latvia, New Zealand, and Norway) falls within this category; these are countries that overuse the services provided by their forest ecosystems, primarily for export purposes. It can thus be said that, for these countries, the use of forest services is driven by demand from abroad.
4. $EF_C > BC$ and $EF_P > BC$: this is the most common situation where the majority of countries fall. It indicates a situation in which the harvest of forest ESs is higher than the local supply (as measured via the biocapacity) and coupled with imports from other countries to meet national demands.

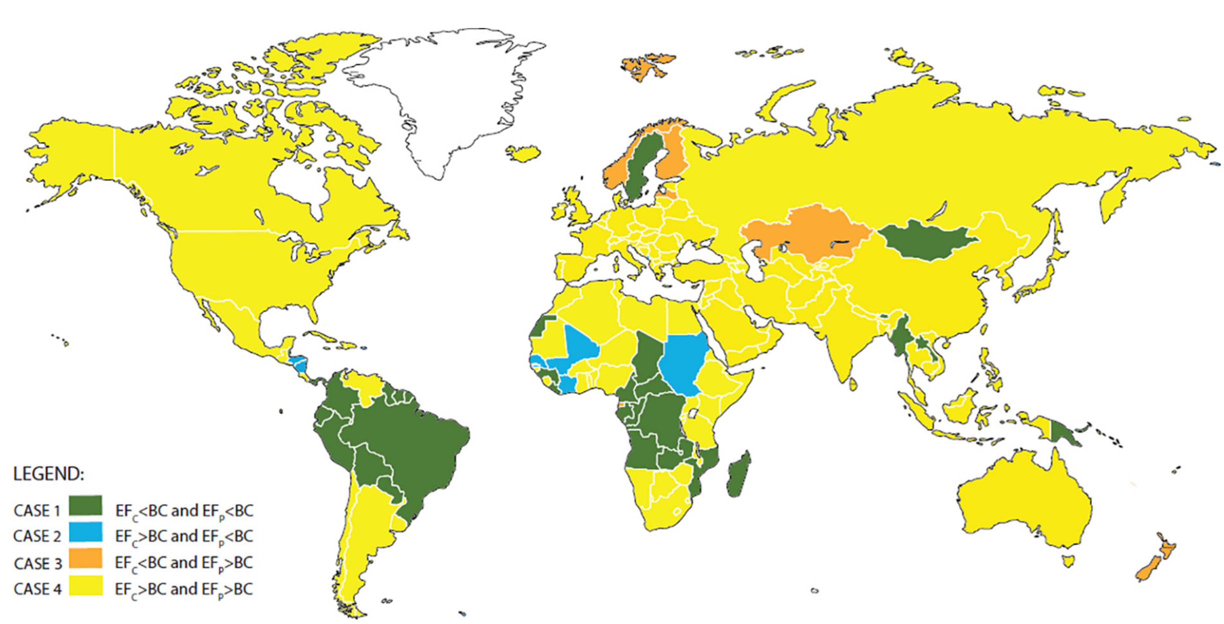

Fig. 3. World distribution of the four cases identified in this study. EF_C is the Ecological Footprint of consumption for the forest plus the carbon Footprint components, EF_P is the Ecological Footprint of production for the forest plus the carbon Footprint components, and BC is the Biocapacity for the forest land type.

4. Conclusions

Ecosystem services are the benefits originating from Earth's natural capital, which sustain the socio-economic human sphere and the well-being of humankind. As the size of the human enterprise continues to increase, there is a need to understand whether such demand stays within or exceeds the carrying capacity of our planet.

The Ecological Footprint method is a biophysical approach capturing – directly or indirectly – some of the basic services on which human societies are built upon and provides otherwise-impossible insight into the human overuse or underuse of such services. As a matter of fact, while the most used monetary valuations only track the Nature's supply dimension of ecosystem services, the Ecological Footprint tracks both their supply from the biosphere and the demand humans place on them - the consumption of ecosystem services – thus providing an ecological balance assessment of those sub-set of ecosystem services.

By comparing a monetary valuation with a Footprint assessment in relation to two specific ecosystem services from forests (i.e. raw material provision and climate regulation), a strong correlation between one of the Ecological Footprint metric (i.e. the biocapacity, BC) and the economic value was found. This represents an important evidence for supporting the Ecological Footprint accounting as a complementary biophysical measure for the supply of such ecosystem services.

Moreover, compared to other biophysical accounting methods, Ecological Footprint accounting has the advantage to express multiple flows of ecosystem services into a common surface equivalent metric, thus facilitating the comprehension and communication of results and providing an overarching macro-ecological picture of the pressures human activities place on specific ecological assets. Being based on physical and biological parameters, Footprint assessments can also be considered less biased than the monetary valuations, which are affected by market price variability and individuals' preferences.

Nevertheless, compared to monetary valuations characterized by a higher flexibility in analyzing various ranges of ecosystem services, the Ecological Footprint framework is limited to tracking only a sub-set of provisioning and regulating services, specifically those based on biologically productive areas. This is acknowledged to be a limitation of the way the Footprint methodology is currently being implemented. However, we argue that such limitation in the services tracked by the Footprint methodology is not an insurmountable theoretical one, but rather determined by the limited investigation and use of this accounting methodology within the ecosystem services' community. We hope that this article can help shedding light on the rationale and framework of the Ecological Footprint methodology and its potential usefulness for ecosystem services assessments and thus stimulate future research aimed at populating the existing methodological framework (characterized by the surface-equivalent approach) with a wider range of ecosystem services.

We believe that the Ecological Footprint could represent a potentially useful approach to provide a quantitative biophysical assessment of ecosystem services, but that further research is needed – involving both the Footprint and the ecosystem services communities – to broaden the range of services this methodology is able to track. Nonetheless, we also acknowledge that the Ecological Footprint is not - and will likely never be - the panacea for a comprehensive ecosystem services' accounting system and it should thus be complemented by, and jointly used with, other indicators to physically and economically account for the whole range of ecosystem services.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecoser.2018.01.010.

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