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Short communication

Validity and utility of ecological footprint accounting: A state-of-the-art review

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ABSTRACT

As with concerns of increasing environmental degradation, research on environmental sustainability is growing in importance. The Ecological Footprint (EF) metric is a resource accounting tool that is widely applied in analyzing sustainable development. This paper was set to assess the overall robustness of EF for sustainability decision-making and discuss proposed changes for improvement of EF as a sustainability indicator. Although EF is advantageous over other methodologies for sustainability analysis with a quantifiable index, it still shows limitations for analyzing certain critical environmental issues such as excessive land use, renewable resource depletion as well as inaccurate measurement of carbon footprint, which is the most important component of EF. Proposed improvements to EF accounting to make a robust indicator and enable a reliable assessment to support sustainable development include the introduction of a correction factor for biocapacity measurement, which facilitates the moderate use of productive lands to limit land degradation. Moreover, the development of a three-dimensional ecological footprint model assists the differentiation of resource stocks from resource flows to help mitigate resource depletion. Furthermore, a modified carbon footprint measurement improves the accuracy of the EF value. Current applications of the improved EF methodologies are also discussed.

1. Introduction

Over the past decades, human activities have caused an extreme decline in natural capital stocks and ecosystem services, on a global scale (Oosthoek and Gills, 2005). Therefore, since the early 90s, various indicators have been developed to evaluate the balance between humanity's demands of resources and nature's supply capacity (Azar, Holmberg, & Lindgren, 1996; Gilbert, 1996; Ragas et al., 1995). Ecological Footprint (EF), as one of the sustainable development indicators, has received significant attention across the worldwide (Blomqvist, 2013; Erb, 2004; Hoekstra, 2009; Hubacek and Guan, 2009). The original concept of EF was introduced by Rees and Wackernagel in the 1990s (Rees, 1992; Rees, 2002; Wackernagel, 1998). EF is a resource accounting tool for evaluating sustainable development in a quantitative way. It is used to seek human demand on an ecosystem's biological resource flow and compares that demand with the ecosystem's capacity to generate these flows. That is also the unique characteristic of EF differentiating it from other indicators. As a single indicator, EF, however, cannot completely measure sustainability; it measures one main aspect of sustainability only (Lin, Wackernagel, Galli, & Kelly, 2015). The EF method categorizes renewable natural resources into a set of six land type areas, namely cropland, forest land, grazing land, fishing grounds, built up land and carbon uptake land. For these land type areas, the more natural resources consumed and carbon waste generated, the bigger their footprint size. On the supply side, Biocapacity (BC) is real productive land area weighted according to relative global bioproductivity. The amount of resource demand and waste generation (EF) should not exceed the supply capacity (BC), which is an essential precondition for achieving sustainable development based on the EF framework. The gap between human consumption and natural supply could be clarified according to EF accounting. It also supports policy planning for decision-makers and seeks to raise public awareness of reducing resource consumption and boost utilization efficiency. EF accounting can have multiple-functions, and is applied in different contexts (Bastianoni et al., 2012a), for instance, in territorial systems such as nations, cities and institutions (Lo-Iacono-Ferreira, Torregrosa-López, & Capuz-Rizo, 2016; Marchettini, Niccolucci, Pulselli, & Tiezzi, 2007; Rugani, Roviani, Hild, Schmitt, & Benetto, 2014); products such as food and buildings (Bastianoni, Galli, Pulselli, & Niccolucci, 2007; Parker and Tyedmers, 2012); services such as industrial processes and tourism (Castellani and Sala, 2012; Mikul & ić, Cabezas, Vujanović, & Duić, 2016).

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As a popular sustainability accounting tool, EF has many strengths: benchmarking human demand for renewable resources and carbon uptake capacity with nature's supply, an aggregated assessment of multiple anthropogenic pressures and facilitating communication with the public. However, a number of critical reflections on the EF concept indicate that: (i) the concept does not closely correlate with the real ecosystem value. For example, species scarcity, habitat uniqueness and excessive land use cannot be identified in the footprint framework, which thus, result in incorrect biocapacity values and, thus, causing ecological problems (Fiala, 2008); (ii) Water is an essential renewable resource, but is only indirectly addressed in the EF approach, and not regarded as one of the productive land types (McManus and Haughton, 2006); (iii) The estimation of carbon waste uptake rate is highly uncertain (Blomqvist et al., 2013), especially considering the fact that carbon footprint is the most rapidly growing portion and takes up to 54 percent of humanity's overall EF (WWF, 2014). Therefore, work on improving the EF accounting is burgeoning in the area of footprint research.

This article presents a review of the usefulness or otherwise of EF as an indicator for sustainability accounting. Furthermore, the article reviews all pertinent modifications to the EF methodology to date for enhancing sustainability decision-making. The reviewing is based on a comprehensive literature search carried out predominantly with the help of the literature database of ISI Web of Knowledge, version 5.23 (www.webofknowledge.com). Search terms were restricted to publications from 2008 to date. Grey literature and reports were also assessed, but an attempt was made to find the same information in more easily accessible journal articles.

The article is organized into the following sections: Section 2 presents a brief review of the EF accounting framework. The main shortcomings of the current EF model and corresponding improved models are presented in Section 3. Discussion of the improved models is provided in Section 4 and conclusions are drawn in Section 5.

2. EF framework: an overview

2.1. Framework of current EF accounting

In order to make human demands on resources and natural capacity comparable, consumed products (for instance food, timber and animal products) are aggregated into ecological footprint and productive land areas are aggregated into a biocapacity value. According to the EF methodology paper (Borucke et al., 2013), the EF framework is composed of six land types: (i) plant-based food and fiber products (cropland), (ii) animal-based food and other animal products (grazing land), (iii) fish-based food products (fishing grounds), (iv) timber and other forest products (forestland), (v) the absorption of carbon dioxide emissions (carbon uptake land), and (vi) the provision of physical space for shelter and other infrastructure (built-up areas). Based on each of the above mentioned distinct land use types, EF values are given and aggregated into a single value. For example, the footprint of potato production by a country is calculated as the area of potato cropland that would be required to produce the harvested quantity at world average yields. The footprints of other grains are calculated in the same way and added together to obtain the total cropland footprint. A similar approach is adopted for grazing, fishing and forest lands footprint calculations. The method for calculating the footprint of carbon and built-up lands is a little different, the detailed methodology of which can be found in Borucke et al. (2013).

Carbon uptake land describes how much of forest land area is required to absorb carbon dioxide emissions from anthropogenic activities. Built-up areas afford shelter space for a given population and are assumed to be constructed on cropland. The remaining four land types provide human renewable natural resources: food crops, animal products and wood.

The unit of EF and BC is global hectares (gha), as expressed by the world average bioproductive area. The global hectare can give consideration to different ecological productions and various inherent capacities among all land use types all over the world. Based on the unique functions, global hectares make EF and BC comparable among different countries. Consequently, if the EF exceeds BC, it implies ecological deficit; otherwise, an ecological surplus is sustained. According to the methodology paper (Borucke et al., 2013), EF is calculated in Eq. (1):

$$\mathrm{EF} = \Sigma_i^n \frac{\mathrm{Pi}}{\mathrm{Y_{W,i}}} \cdot \mathrm{EQF_i} \tag{1}$$

where $\mathrm{P_i}$ is the consumed amount of each product i (in t $\mathrm{yr^{-1}}$); $\mathrm{Y_{w,i}}$ is the average world annual yield for the product i (or carbon dioxide absorbing capacity); $\mathrm{EQF_i}$ is the equivalence factor for the land use type producing products i.

BC measures the amount of biologically productive land and sea area available to provide the ecosystem services that humanity consumes, and is the counterpart concept of EF. BC, however, may vary from time to time depending on local climate and management. BC is calculated as shown in Eq. (2):

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

Where $\mathrm{A_{N,i}}$ is the bioproductive area that is available for the production of each product i; $\mathrm{YF_{N,i}}$ is the national specific yield factor for the land producing product i; $\mathrm{EQF_i}$ is the equivalence factor for the land use type producing each product i.

Yield factor (YF) is a country-specific coefficient, relative to different land use types and production of each year. The yield factor is calculated annually according to the following Eq. (3):

$$\mathrm{YF} = \frac{\mathrm{Y_L}}{\mathrm{Y_W}} \tag{3}$$

where $\mathrm{Y_L}$ is local average yield for a given land use type for the same product; $\mathrm{Y_W}$ is the world average yield for a given land use type for the same product.

Equivalence factor (EQF) is used to convert a particular land use type into a unified unit for a bioproductive land area to make the land use types comparable, as measured in global hectares (Wackernagel & Rees, 1998). Equivalence factors reflect the inherent capacity of each land use type.

2.2. Heated debate on EF accounting

The EF model is very popular with scientific journals, environmental organizations, and the media. Its popularity is not only because of the unique context but also that EF accounting is one of the hottest debate topics in scientific journals today. The concept has generated a series of back-and-forth debate in various fora with the number of critical and reply articles published on the subject burgeoning within a short time. Ongoing critical discussions have seen the exchange of several letters, replies and articles in which the conceptual and methodological aspects of EF have been discussed, mostly in the same journal (e.g., see Giampietro and Saltelli, 2014a, 2014b; Goldfinger, Wackernagel, Galli, Lazarus, & Lin, 2014; Lin et al., 2015; van den Bergh & Grazi, 2015) within a few months and vice-versa. Therefore, the debate on EF is considerably intense. Overall, the debate highlights divergent opinions from two schools of thought that however, stems from a common point of departure. On the one hand, one school of thought argues that Ecological Footprint Accounting adds up the ecological services that humans demand, in as far as they compete for biologically productive space. According to this claim, the Ecological Footprint can be compared against BC, the available bioproductive area, which provides these services (Borucke et al., 2013). On the other hand, another school of thought argues that the Ecological Footprint is not a quantitative approach capable of measuring human demand on nature against nature's ability to provide ecological services and that

Table 1
Summary of the major points of debate on Ecological Footprint Accounting.

Major points of debate	Reference
Sustaining intensive production in EF concept will make Biocapacity erroneous; Important environmental limitations are not addressed in EF.	Fiala (2008)
EF concept provides minimum criteria for sustainability, not a guarantee of it; EF is a compound indicator reflecting complex interactions and cannot capture every aspect of sustainability.	Kitzes and Moran (2009)
EF figures indicate a sustainable consumption except carbon footprint, which go against many ecosystem studies; carbon footprint is unreliable since it is based on assumed forests carbon sequestration rate; limited policy utility of EF guidance.	Blomqvist et al. (2013)
EF does not reflect resource depletion due to unavailability of globally consistent data sets; carbon footprint is based on current best estimates of actually average sequestration rates.	Rees and Wackernagel (2013)
EF is in contradiction with its intended meaning and actual accounting results.	Giampietro and Saltelli (2014a)
The real implication of EF is different from that considered by Giampietro and Saltelli: demand indicator vs hybrid pressure plus-impact indicator; predictive tool vs descriptive indicator.	Goldfinger et al. (2014)
EF is inconsistent with its stated purpose of measuring demand on ecosystems; EF depends mostly from a dimensionally flawed energy emissions assessment; EF is optimistic at the global scale and policy-misleading at the local one; EF should not be based on the simplifications typical of reductionism.	Giampietro and Saltelli (2014b)
Different environmental issues cannot be aggregated into a single land indicator; EF approach is not policy relevant.	van den Bergh and Grazi (2014a)
EF approach is based on real areas and is relevant to policy concerns.	Wackernagel (2014)
Most shortcomings of EF are not illustrated in the reply by Wackernagel (2014).	van Den Bergh and Grazi (2014b)
EF is informative and evolving.	Lin et al. (2015)
EF simplifies environmental situations.	van den Bergh and Grazi (2015)

the results generated by this methodology are not useful. A summary of criticisms and rebuttals published in recent years is presented in Table 1.

3. Modification of EF models for various purposes

3.1. EF for analyzing excessive land use

According to Fiala (2008), EF was considered to be “bad economics and bad environmental science”. One of the important reasons for these comments was that requiring high biocapacity, especially on cropland, may bring about excessive land use and even cause land degradation. In the EF concept, high productivity of the various land use types results in high biocapacity, which is considered positive for sustainability. However, if a population uses an area much too intensively to achieve high yields, land degradation will be unavoidable. It is increasingly evident that tolerating land degradation is expensive, both to individual owners and the whole society, especially in the long run (Turner et al., 2016). Land degradation could be caused by human-dominated actions such as over- cultivation (Andersson, Brogaard, & Olsson, 2011; Lambin et al., 2001). Based on experiences from agriculture, excessive use of farm-land leads to precious topsoil eroding away and weakening soil fertility. If productive lands are kept in over-use, it could appear to be moving toward sustainability while, in fact, that may actually be far-fetched.

The EF is an accounting tool for quantifying Daly's principles of sustainability. From the point of view of excessive land use, EF cannot fully represent the original intention of sustainable development (Giampietro and Saltelli, 2014a).

In a reply article to Fiala (2008), Kitzes and Moran (2009) pointed out that EF is a composite indicator and essential for the decision-making process, even though it cannot capture every aspect of sustainability. Therefore, Bastianoni, Niccolucci, Pulselli, and Marchettini (2012b) proposed a correction factor τ (Eq. (4)) embedded in the current BC measurement formula. In theory, the improved method could overcome the limitation of EF that potentially lead to intensive land use and even causing land degradation.

The correction factor τ is used to modify the biocapacity calculation. According to Bastianoni et al. (2012b) sufficient land recovery time is a precondition for maintaining land productivity in the long run. However, recovery time is ignored in the footprint approach. In order to capture biocapacity loss, τ is added for sustainable land management and calculated as (Eq. (4)):

$$\tau = \frac{T_{\mathrm{use}}}{T_{\mathrm{recovery}}} \tag{4}$$

where T_{use} is the time of effective use of the land; T_{recovery} is the time for topsoil to regenerate, T_{use} and T_{recovery} are measured in years. In the farmland case τ is set to be 1/12. Biocapacity is calculated in Eq. (2), in the classic EF approach. However, for sustainable cultivation, only 1/12 of the area should be cultivated to keep the land productive. Thus, the biocapacity calculation is modified to:

$$\mathrm{BC} = \Sigma_i A_i \cdot \tau \cdot \mathrm{YF}_i \cdot \mathrm{EQF}_i \tag{5}$$

The modified BC measurement takes land recovery time into account and helps to utilize bioproductive lands in a sustainable way through the provision of plenty of recovery time. The correction factor is especially useful for cropland and fishing land. Overuse of bioproductive land will lead to future biocapacity loss, and the correction factor could overcome the problem of neglecting overexploitation in the footprint approach.

The EF framework with correction factor aims to consider land's capability to capture suitable biocapacity for maintaining long-term productivity. However, at present, no applications of the EF method with the correction factor can be found. The timeframe of intensive land use is quite specific and depends extremely on local conditions. Land recovery time is also difficult to standardize not only because of complex plantation growth and fish reproduction patterns but also because it depends on local consumption requirement. A large population has high demands, resulting unavoidably, in intensive land use. Therefore, the new model might not be applied in practice at present. Nevertheless, this model provides a new solution for correlating EF with intensive land use.

3.2. EF for assessing resource depletion

Ecosystems are considerably crucial for humanity since they provide us with precious ecological resources and services. Resource stocks could generate resource flows such as visible resources and invisible services (Daly, 1994). The conventional EF and BC models track whether the amount of biologically productive space is sufficient for the requirements of a given population through the differences in real resource flows, but not by monitoring the changes in resource stocks. Therefore, resource flows with a finite regeneration capacity needs to be carefully managed. Excessive consumption of resources is at the cost of resource stocks. However, maintaining resource stocks is a precondition for sustainable development and resource depletion might severely affect natural circulation (Costanza and Daly, 1992; Wackernagel and Rees, 1997). For the sustainable use of natural resources, humans should "live on the interest of the natural capital," which refers to resource flows generated by stock, the depletion of which will affect the well-being of future generation's (Wackernagel, 1994). According to Niccolucci, Bastianoni, Tiezzi, Wackernagel, & Marchettini (2009) resource stock has been depleted since 1988, and if resource depletion keeps growing, a tremendous amount of debt will be accumulated, which can never be paid back by natural capital flows (Fang, Heijungs, & Snoo, 2014; Wackernagel and Rees, 1997). Therefore, it is crucial to clarify resource depletion associated with resource usage instead of total resource consumption in the current EF accounting.

Consequently, Niccolucci et al. (2011) developed the classic EF method to a three-dimensional EF (^{3D}EF) model, which could differentiate natural capital stocks and resource flows. The ^{3D}EF is composed of two relative indexes: EF size (EF_{size}) and EF depth (EF_{depth}). EF_{size} accounts for the annual human consumption of natural resource flows and EF_{depth} stands for natural stock depletion. The value of EF_{depth} is set to one if a given population uses natural resource flow without damaging resource stock. In this case, human metabolism is within the resource regeneration rate, in line with the sustainable development principle, according to Daly's sustainability theory (Daly, 1990). The values of the classic EF and ^{3D}EF are numerically identical. The value of EF_{depth} started to increase gradually since the resource consumption rate exceeded the regeneration rate in 1988. In fact, the EF_{depth} reached 1.44 in 2006, which means 1.44 years are required to regenerate the resources for one-year's consumption (Niccolucci et al., 2011).

Overall, the ^{3D}EF model provides a possible solution to trace pressures on natural capital flows or natural capital stocks and clarifies resource consumption between current and future generations. Besides, the ^{3D}EF model provides decision-makers with a comprehensive resource utilization status. For instance, a bigger EF_{size} or higher GDP of a country may base on stock depletion. Therefore, increasing the efficiency of resource utilization rate and putting emphasis on international trade may relieve the local resource depletion status (Galli, Wackernagel, Iha, & Lazarus, 2014). Principally, while the ^{3D}EF model inherited from the current EF framework, it is more suitable for considering the concept of sustainability.

3.3. Modification of the key component of EF–carbon footprint

Of the six land use types, carbon uptake land is the most rapidly-growing component and accounted for 54% of the overall EF in 2007 (WWF, 2014). It is noted that the ecosystems could only absorb a finite amount of carbon wastes. Excessive carbon emissions will, first and foremost, result in climate change, which is a global problem (Wackernagel, 2011). Since the most significant influence of anthropogenic activities on natural ecosystems is that of carbon dioxide emissions, a method for calculating the land area required for carbon dioxide sequestration have been developed (Monfreda, Wackernagel, & Deumling, 2004). Also, the Global Footprint Network developed a model for estimating the forest area needed for absorbing carbon wastes (Borucke et al., 2013), which was revised recently (Mancini et al., 2016), aiming to increase its accuracy for carbon footprint calculation.

Furthermore, a slew of critical reviews on carbon quantity assessment are published, which include: transforming carbon emissions into additional areas of forest is reasonless (van Den Bergh & Grazi, 2014a); carbon sequestration rate setting cannot reflect real conditions well (Blomqvist et al., 2013); carbon sequestration capacity depends strongly on the unknown factors like carbon absorption capacity of specific forest types and ocean deposition conditions. It is, thus, believed that the carbon footprint value misses its intended function (Giampietro and Saltelli, 2014a).

In carbon footprint measurement, the accuracy of the carbon sequestration rate calculation plays a vital role. Even though the usefulness of the EF method of transforming carbon emissions into forest area is doubted by EF opponents, the function of forests as for carbon sinks is approved by many international organizations, including the Intergovernmental Panel Climate Change (IPCC) and Food and Agriculture Organization (FAO). In fact, when analyzing the model of carbon dioxide conversion between the atmosphere and forest biomes, many researchers focus on the quantity of carbon emission sequestered: the world's forests have sequestered half of human-induced carbon waste (Pan et al., 2011).

In the current EF model, the carbon footprint value depends greatly on the key parameter of Average Forest Carbon Sequestration (AFCS). The higher the forest sequestration capacity, the lower the carbon footprint of human demand. The AFCS value is retrieved from the IPCC report (Ewing et al., 2010) and the default value is 0.97 t C wha^{-1} yr^{-1}(Lazarus et al., 2016). Since annual forest biomass growth, biomass loss and forest area vary from year to year, the key factor should be adopted according to the prevailing local conditions. The AFCS value has been validated based on an extensive dataset of carbon cycling in the forest biome. Besides some parameters already used in the classic model (forest area, forest type and ocean sequestration) (Borucke et al., 2013), the new model (Mancini et al., 2016) also includes vital factors such as forest biomass growth and loss, soil respiration, and harvested wood products that indeed exist in an ecosystem and social system. It turns out that less carbon wastes are sequestrated by the forest in reality than the original model predicts. The revised AFCS model (Mancini et al., 2016) involves several important forest factors and is more accurate than the original one.

Table 2
Comparison of conventional and improved EF methods.

Weaknesses of conventional EF	Proposed Improved Methods	Main Feature of Improved Methods	Applications of Improved Methods
Pursuit of high biocapacity may result in excessive land use and even cause land degradation	Biocapacity calculation with correction factor	-Correction factor will decrease Biocapacity value based on land recovery time to maintain productivity -Value of correction factor depends on specific cases without standardized uptake value	Not retrieved
Renewable resource flow and natural capital stock cannot be differentiated	^{3D}EF	-Resource flow and capital stock is determined by EF_{size} and EF_{depth} -Data availability is same as for the current EF accounting	Galli, Halle, and Grunewald (2015) Peng et al. (2015)
Carbon footprint measurement is not accurate since carbon sequestration rate cannot reflect real conditions well	Refined carbon footprint measurement	-The value of AFCS is corrected with forest biomass growth and loss, soil respiration etc. -Accuracy of carbon sequestration rate is increased.	Musikavong and Gheewala (2017a) Musikavong and Gheewala (2017b)

4. Discussion

Based on the weaknesses of EF accounting raised and review of the proposed improvements presented above (summarized in Table 2), it is clearly illustrated that EF accounting is a work in progress from when it was conceived till now. Some limitations could be compensated with new improvements even though they might not be applied in practice immediately. There is no doubt that EF accounting could provide a resource consumption monitoring ability and advise on human pressure reduction on ecosystems.

4.1. Improved EF model

EF model modification and performance tests are considerably vital. The improved EF models mentioned above demonstrate various superiorities in comparison to the classic one. The modified model with correction factor is considered for cropland, fishing grounds, grazing land and forest. It highlights the necessity to maintain the recovery time of productive lands to sustain production capacity. According to this model, land usage should be kept moderate, and the pursuit of maximum production yield should not be the only target for humans. Furthermore, measuring BC with the proposed correction factor leads to the realization that the classic BC is overvalued and that overexploitation might be overlooked. However, the EF method with correction factor is still a theoretical model at present. Few case studies on EF with the correction factor have been published, most probably because source data are not available.

On the other hand, the modified ^{3D}EF model is suitable for assessing the sustainability of territorial systems like countries or cities. The ^{3D}EF model is developed based on extension and modification of the classic one. It provides new insights to the quantitative measurement of natural capital stocks depletion and is quite vital for maintaining future biocapacity. Nevertheless, there are still limitations to the ^{3D}EF: detailed influence of resource depletion on biocapacity is undefined and different stock depletion gradings need to be identified based on different EF_{depth} values.

The modified carbon footprint calculation method has the same application range as the classic one. Nevertheless, with the improved model, a more precise footprint area demand could be obtained, making EF a robust, sustainable indicator.

4.2. Multi-indicator approach

EF is also combined with other assessment concepts or models to get a comprehensive evaluation result for sustainability. For example, Cerutti, Bruun, Beccaro, and Bounous (2011) summarized four assessment indicators, Life cycle assessment, Ecological Footprint, Emergy and Energy Balance, on fruit production with the aim of tracking the environmental burden of fruit crops and improving environmental performance. Although the usage of different assessment indicators results in different conclusions, abundant reference information is summed up, which illustrate the environmental impact of fruit crops, especially in orchard systems. Furthermore, EF and many other sustainability indicators could be used together to evaluate products or services. For instance, EF and Emergy are used to measure the energy consumption and CO_2 emissions of different cement manufacturing processes (Mikulčić et al., 2016). Findings indicated that Emergy accounting for regular cement production and that with three mitigating scenarios (with energy efficient kiln, with alternative fuels, and combined efficient kiln and alternative fuels scenario) do not vary significantly. However, the combined scenario has the lowest resource demand and lowest CO_2 emission. Moreover, EF, Emergy and Greenhouse Gas Inventory methods were jointly used to measure the environmental sustainability of five Italian provinces (Marchettini et al., 2007). Findings indicated that the Province of Siena was the most sustainable area, which has the lowest value of total Emergy flow, Ecological Deficit and per capita CO_2 emissions. Furthermore, except for assessing products or services with more than one sustainability indicator and comparing results, Pereira and Ortega (2012) proposed an integrated indicator of EF and Emergy, trying to make their respective advantages complementary to each other and, thus, proposed a new assessment model, Ecological Footprint using Emergy Synthesis. The model firstly converts energy or mass embedded in a product or service to emergy through an emergy intensity factor. Secondly, emergy flow is converted to area units through a global empower density. Therefore, more stable ecological deficit/reserve results are achieved compared to the classic EF. In other words, combining the method of EF with other assessment models could provide a consolidated scientific foundation by providing several evaluation indicators.

There are several sustainability evaluation indexes with footprint concepts: ecological footprint, carbon footprint and water footprint, which constitute the footprint family proposed by Galli et al. (2012). Since a single footprint indicator is insufficient to process an integrated environmental assessment, implementation of the footprint family could expand the sustainability assessment scope, and composite human pressure could be tracked. The EUREAPA online database provides EF, carbon and water footprint values of 45 countries and 57 consumption sectors with the aim to provide comprehensive evidence for sustainable consumption and production (Roelich, Owen, Thompson, Dawkins, & West, 2014).

5. Conclusions

The major strengths of the EF method make it widely applicable in the development plans of several national or subnational governments (Bastianoni et al., 2012a). Similar to other assessment metrics, EF is intended to capture and summarize complicated and large-scale phenomena in a simplified and accurate way. Balancing the limitations and benefits is significantly essential for utility of this metric (Blomqvist et al., 2013).

This paper summarized three essential limitations of the current EF methodology and discussed the corresponding proposed improved methods. At first, an improved EF model with the introduction of a correction factor for calculating biocapacity is proposed, which considers land recovery time and corrected biocapacity with lower values than that obtained with the original EF method. Secondly, the improved method of ^{3D}EF model specifies EF_{size} for resource flow and EF_{depth} for natural resource stocks. Ecological pressures on natural capital stocks could be identified through the ^{3D}EF model. Finally, in a refined carbon footprint calculation, a key factor of AFCS was modified under different forest types. A more precise carbon footprint value could be achieved with the updated model. Overall, EF accounting is seen as a work in progress and needs to be continually perfected and developed.

Along with the growing global attention to EF, more applications and novel improved methodologies of the indicator has been published. The EF model combined with other assessment indicators and footprint family concepts are becoming new development trends. Based on the advantages of each modified EF model and other indicators, a combined improved footprint system could be introduced with other developed sustainable approaches. Continued development of the EF will provide a robust sustainability indicator that guides governments, businesses and individuals to manage natural resources efficiently and approach sustainability.

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