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Ecological Footprint: Refining the carbon Footprint calculation

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ABSTRACT

Within the Ecological Footprint methodology, the carbon Footprint component is defined as the regenerative forest capacity required to sequester the anthropogenic carbon dioxide emissions that is not absorbed by oceans. A key parameter of the carbon Footprint is the Average Forest Carbon Sequestration (AFCS), which is calculated from the net carbon sequestration capacity of forests ecosystems.

The aim of this paper is to increase the clarity and transparency of the Ecological Footprint by reviewing the rationale and methodology behind the carbon Footprint component, and updating a key factor in its calculation, the AFCS. Multiple calculation options have been set to capture different rates of carbon sequestration depending on the degree of human management of three types of forest considered (primary forests, other naturally regenerated forests and planted forests). Carbon emissions related to forest wildfires and soil as well as harvested wood product have been included for the first time in this update of the AFCS calculation. Overall, a AFCS value range of $0.73 \pm 0.37\,\mathrm{t\,C\,ha^{-1}\,yr^{-1}}$ has been identified. The resulting carbon Footprint and Ecological Footprint values have then been evaluated based on this value range. Results confirm that human demand for ecosystem services is beyond the biosphere's natural capacity to provide them.

1. Introduction

The biophysical limits of our planet represent one key aspect of sustainability. The Earth is a finite, materially closed system and as such, it is regulated by thermodynamic laws which define limits on natural resources production and waste absorption (Ehrlich, 1982; Georgescu-Roegen, 1971; Meadows et al., 1972; Pulselli et al., 2008; Tiezzi, 1984). Nevertheless, over the last half century, humanity has experienced significant economic growth, which has lead from an "empty-world economics" into a "full-world economics", where the natural resources are becoming increasingly limited (Daly, 1990) and where natural ecosystems and biodiversity are being compromised (Lenzen et al., 2012; LPR, 2012; Butchart et al., 2010; Ellis et al., 2010; MEA, 2005).

Many scientists argue that humanity is likely beyond safe operating limits in key planetary systems (e.g., Bradshaw and Brook, 2014; Crutzen, 2002; Rockström et al., 2009), that a planetary-scale critical transition might already be approaching (e.g., Barnosky et al., 2012; Steffen et al., 2007) and that the global economy has likely passed "a sustainable well-being" threshold (Kitzes et al., 2008a; Max-Neef, 1995; Niccolucci et al., 2007, 2012). Tools are thus needed to determine the extent to which humanity's demand remains within or exceeds the limits of what the Earth's natural capital can provide as well as to detect early warning signs and potentially forecast the consequences of human-induced pressures on ecosystems (Bauler, 2012; Moldan et al., 2012).

Introduced in the 1990s by Mathis Wackernagel and William Rees (Wackernagel, 1994; Wackernagel and Rees, 1996), the Ecological Footprint is an indicator which can be used to track past and current human pressure on the biosphere's capacity to provide life-supporting and regulatory ecosystem products and services (Galli et al., 2014; Wackernagel et al., 1999; Monfreda et al., 2004). As such, it can be used to provide a first quantitative assessment of the two sustainability principles identified by Daly (1990): that the Earth's regenerative capacity for natural resources should not be exceeded by human harvesting rates and that waste emission rates should not exceed the natural assimilative capacity (Goldfinger et al., 2014; Galli, 2015).

According to the National Footprint Accounts (hereafter NFA) 2014 Edition, the official Ecological Footprint assessments at world and national level, humanity demanded the resources and services of 1.5 planets in 2010 (WWF et al., 2014). Of the six land

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types considered by this accounting tool (see Section 2.1), the carbon Footprint component (i.e., the bio-productive land required to sequester anthropogenic carbon dioxide emissions. See Section 2.1) was the largest one, making up approximately 54% of humanity's total Ecological Footprint. Because of its noticeable contribution, this component of the Ecological Footprint has been increasingly scrutinized (Ayres, 2000; Kitzes et al., 2009; Neumayer, 2013; Wackernagel and Silverstein, 2000; Wiedmann and Barrett, 2010) and critically reviewed (van den Bergh and Verbruggen, 1999; van den Bergh and Grazi, 2013; Giampietro and Saltelli, 2014; Blomqvist et al., 2013).

In line with Goldfinger et al. (2014), the inclusion of the carbon Footprint component into the overall Ecological Footprint methodology is not put into question in this paper; nonetheless, increased transparency and accuracy in its underlying calculation is needed to ensure that human demand for carbon sequestration is properly quantified and that proper recommendations are derived from using the Ecological Footprint methodology.

Building on a preliminary work by Mancini (2012), this paper aims to shed light on the methodology and parameters used to calculate the carbon component of the Ecological Footprint. The focus is to update a key parameter of this calculation – the Average Forest Carbon Sequestration (hereafter AFCS) – which captures the capacity of a hectare of world-average forest ecosystem to sequester atmospheric carbon dioxide through photosynthesis. Data on the global forested area and the yearly average biomass growth of forest plants are used to perform this AFCS update. The methodology used in this paper considers multiple calculation options and a range of input variables for providing Footprint users with a potential range of AFCS values (see Section 3), which is then compared with the previous value historically used in Footprint accounting. Finally, the resulting values are used to derive ranges for carbon Footprint and total Ecological Footprint.

The work ensues from recommendation given in Kitzes et al. (2009) to keep key constants/parameters with a large influence on the overall Footprint calculation up-to-date through specific additional analyses and periodical reviews. Also, the use of ranges for these constants allows the generation of sensitivity ranges for Footprint results (Kitzes et al., 2009; Niccolucci et al., 2008).

2. Materials and methods

The Ecological Footprint methodology (Wackernagel et al., 2002) is an accounting system which tracks how much of the planet's regenerative capacity humans demand to produce resources and to sequester waste, and compares this to the planet's available regenerative capacity. Carbon dioxide emissions from fossil fuel combustion represent the sole waste flow directly tracked by the Ecological Footprint due to difficulties to refer other waste impacts to any regenerative capacity of biological surfaces as discussed in detail in Kitzes and Wackernagel (2009) and Kitzes et al. (2009).

The accounting framework is composed of two measures: Ecological Footprint, the demand that humans place on bioproductive areas, and biocapacity, the nature's availability to provide the resources and ecosystem services that are annually consumed by humans (Borucke et al., 2013). Both metrics are expressed in terms of comparable equivalent land units, namely global hectares (gha), hectares of land or water normalized to have the world-average productivity of all biological productive land and water in a given year (Galli et al., 2007; Galli, 2015).

The biocapacity (BC) in each nation is calculated as in Eq. (1):

$$BC = \sum_i A_i \times YF_i \times EQF_i \tag{1}$$

where

- A_i represents the estimated bioproductive area that is available for the product i at the national level;
- YF_i is the nation-specific yield factor for the production of product i;
- EQF_i is the equivalence factor of the land producing each flow i.

On the other hand, the Ecological Footprint of each nation is calculated as in Eq. (2):

$$EF = \sum_i \frac{T_i}{Y_{W_i}} \times EQF_i \tag{2}$$

where:

- T_i is the annual amount of tons (t yr^{-1}) of each product (or waste) flow i that are consumed (or released) in the nation;
- Y_w is the annual world-average yield[1] (t wha^{-1} yr^{-1}) for the production (or sequestration) of each flow i.
- EQF_i equivalence factor of the land producing each flow i.

The use of Yield Factors (YFs) and Equivalence Factors (EQFs) allows the conversion of physical hectares into global hectares (gha). YFs capture the difference between national and world-average productivity within a given land-use category, and EQFs weight different land types based on their inherent capacity to produce human useful biological resources with relation to the global average productivity across all land types. The weighting is based on agricultural suitability indexes from the Global Agro-Ecological Zone (GAEZ) model (FAO and IIASA, 2000). See Borucke et al. (2013) and Galli et al. (2007) for a detailed description of the Ecological Footprint and biocapacity calculation methodology.

According to the World Conservation Union classification (World Conservation Union et al., 1991), the bioproductive areas available to support human life can be divided into five main types and include: cropland, grazing land, fishing ground, to produce plant-, animal- and fish-based products respectively; forest, for wood products and sequestration of carbon dioxide; and built-up areas, the space for shelter and others infrastructures which competes for biologically productive space.

At its core, biocapacity reflects the ability of autotrophic organisms to capture energy from the sun via photosynthesis, and use this energy to concentrate and structure matter into resources annually available for human use. While biocapacity accounts for nature's ability to regenerate ecological goods and services, the core aim of the Ecological Footprint is to account for humanity's demand for ecological goods and services (Galli, 2015). Here we focus on the carbon Footprint component.

2.1. Methodology for calculating the carbon Footprint component

Within the Ecological Footprint methodology, the carbon Footprint is the amount of bio-productive forest land required to sequester anthropogenic carbon dioxide emissions, at world-average sequestration rate, to avoid CO_2 accumulation in the atmosphere.[2] This should not be confused with the term "Carbon

[1] The prefix 'w', and later also the 'g' of global hectares, is indicative of a weighted unit, but it is not a unit itself. It reflects the quality, geographical location and productivity of the hectare, not the quantity (Galli et al., 2007).

[2] The EF methodology does not aim to answer how many trees should be planted to offset carbon under various scenarios (e.g. reforestation) but rather aims to calculate the amount of forest area needed in each year to sequester the actual anthropogenic emissions for that year given the actual forest situation (i.e. forest surface, biomass growth) of that year.