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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.

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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.

Footprint", the newly popular measure used to assess the amount of anthropogenic greenhouse gas emissions expressed in tons of CO_2 equivalent (t $CO_{2\text{-eq}}$) (see for instance EPLCA, 2007; Wiedmann and Minx, 2008). However, Carbon Footprints in tons can easily be translated into area-based carbon Footprints using sequestration rates. More details can be found in Galli et al. (2012).

According to Lazarus et al. (2014), NFA considers three sources of CO_2 emissions from anthropogenic activities, which are derived from the International Energy Agency (IEA, 2010): (i) emissions from fossil fuel combustion by country and economic sector; (ii) emissions from non-fossil fuel sources (gas flaring, anthropogenic forest fires, cement production and unsustainable biofuel production[3]); and (iii) emissions from international marine and aviation transport, named "bunker fuel", which are re-allocated to countries based on their share of import. In 2010, the three sources represent 78%, 19% and 3% respectively of the total anthropogenic CO_2 emissions, which were 38.7 Gt CO_2 (IEA, 2010).

The calculation of the carbon Footprint component (carbon_EF) is based on Eq. (3) (see also Borucke et al., 2013):

$$\text{carbon\_EF} = \frac{P_C \times (S_{OCEAN})}{Y_W} \times EQF \quad \text{with} \quad Y_W = \frac{\text{AFCS}}{0.27} \tag{3}$$

where:

- P_C is the world's annual anthropogenic emissions of carbon dioxide measured in Mt CO_2;
- S_{OCEAN} is the fraction of anthropogenic CO_2 emission sequestered by oceans in a given year. Data from Khatiwala et al. (2009) are currently used in NFA and the oceanic uptake fraction for the year 2010 is 28% (Lazarus et al., 2014; Borucke et al., 2013).
- *EQF* is the equivalence factor used to weight forest land. The current GAEZ-based method (see Section 2) assigns forest land a value of 1.26 (indicating that an hectare of world-average forest is 1.26 times as productive as a world average hectare of land).
- Y_W is the annual rate of carbon dioxide sequestration per hectare of world average forestland.
- AFCS is the average forest carbon sequestration, expressed in t C ha^{-1} yr^{-1};
- 0.27 t C (t CO_2)$^{-1}$ represents the share of C within the CO_2 molecule an it is used to convert tons of carbon into tons of carbon dioxide.

AFCS represents the long-term capacity of a hectare of world-average forest ecosystem to sequester atmospheric carbon dioxide through photosynthesis. It is expressed in tons of carbon per world-average hectare of forest per year (t C wha^{-1} yr^{-1}), and consistent with Kitzes et al. (2008b), can be calculated as:

$$\text{AFCS} = \frac{\text{NFP}}{A_F} \tag{4}$$

where:

- NFP (Net Forest Production) is the total annual production of biomass in forests, expressed in tons of carbon per year (t C yr^{-1}). Depending on the system boundaries under study, NFP can be defined as Gross Primary Production (GPP), Net Primary Production (NPP), Net Ecosystem Production (NEP) and Net Biome Production (NBP) (see Section 2.1.2).
- A_F represents the total forested area on the Earth, expressed in hectares (ha).

[3] According to IEA, unsustainable biofuel production is the part of the total production that is not balanced by biomass re-growth (approximately 10% of total according to IPCC Sink/Source Category 5).

Although all ecosystems have the capacity to store CO_2 in long or short term through photosynthesis, the Ecological Footprint methodology is conservatively calculated from the sequestration capacity of forest ecosystems, which are the predominant terrestrial ecosystems with significant carbon sequestration and long term storage capacity (e.g., Pan et al., 2011; Pregitzer and Euskirchen, 2004). The Ecological Footprint methodology makes the conservative assumption that carbon sequestration, when demanded by humanity, would be achieved using the most efficient land type possible: forest land. (Borucke et al., 2013; Kitzes et al., 2009).

Historically, the average forest sequestration capacity value used in Ecological Footprint accounts (including the most recent NFA 2014 edition) has been 0.97 t C wha^{-1} yr^{-1} (Kitzes et al., 2008b; Lazarus et al., 2014). However, global datasets available for this calculation have now improved greatly, and there is a need to revise this key factor as suggested by Kitzes et al. (2009). Moreover, this historical value was calculated using Net Primary Production (NPP) as the basis for the NFP calculation and therefore without considering other types of carbon exchanges in forest ecosystems.

As explained in the following sections, a new AFCS value is calculated here by using updated datasets and according to the IPCC methodology (IPCC, 2006a), to track greenhouse gas fluxes (emissions and stock changes) between forest ecosystems and the atmosphere. Improving on the previous assessment (Kitzes et al., 2008b; Lazarus et al., 2014), NFP is calculated here as the net sequestered carbon in all the significant pools of forest ecosystems, therefore an approximation of Net Ecosystem Production (NEP) (see Section 2.1.2).

2.1.1. Forested area (A_F)

According to the 2010 Global Forest Resource Assessment report (FAO, 2010), forests are defined as "*Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10%, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use*". They are divided by FAO (2010) into three main classes according to their 'naturalness', which reflects the degree of human management:

- *Primary forest*: naturally regenerated forests of native species, without clearly visible indications of human activities, in which ecological processes are not significantly disturbed. The area of primary forests on Earth is about 1.36 billion ha, 36% of the global forest surface (FAO, 2010). Primary forest is equivalent to the IPCC category "Natural Forest" (IPCC, 2006b).
- *Other naturally regenerated forest*: naturally regenerated forests, with clearly visible indications of human activities. This class has an extension of 2.18 billion ha, 57% of the total surface (FAO, 2010). IPCC does not distinguish this particular land type; as such, we here assume it is equivalent to the IPCC category "Natural Forest" (IPCC, 2006b).
- *Planted forest*: forest predominantly composed of trees established through planting and/or deliberate seeding. Planted forests cover 0.26 billion ha (7% of the global forest surface), of which 24% is set aside for protective uses and the remaining 76% for productive purposes (FAO, 2010) and are equivalent to the IPCC category, "Plantation" (IPCC, 2006b).

These three classes of forest have different carbon sequestration capacity depending on their geographical location and ecological zone. Data on the extent of each ecological zone (e.g. tropical rain forest, temperate continental, boreal coniferous, etc.) in each continent (Africa, Asia, Europe, North and Central America, Oceania, South America) is provided by the 2000 Global Forest Resource Assessment (FAO, 2000). This report also provides data (as percentage) on the share of forested areas in each ecological zone (e.g., Tropical Rain Forest, Temperate Continental, etc.) and for each continent. This data has been used to derive the extent of forest surfaces (in million ha) by ecological zone and continent.

Additional information on the most recent data on area extension by country and continent as well as the breakdown of forest areas into three main classes – *Primary*, *Other naturally regenerated* and *Planted* forests – is provided by the 2010 Global Forest Resource Assessment (FAO, 2010, Table 7, pages 250–255). For each of these classes, this report provides the forest area per each country, without information on the ecological zone.

As such, data from the two editions of the Global Forest Resource Assessment (FAO, 2000, 2010) have been interpolated to derive detailed information on forests coverage by continent, ecological zone and class of forestland and results are reported in Table A4. The classification by ecological zone and continent is consistent with IPCC data classification on biomass growth (IPCC, 2006b).

2.1.2. Net Forest Production (NFP)

Plant biomass growth and the relative increase in plant C stock is the main pathway of CO_2 removal from the atmosphere (IPCC, 2006a). As shown in Fig. 1, carbon fluxes between ecosystem components are defined in several ways (IPCC, 2006a): Gross Primary Production (GPP), Net Primary Production (NPP), Net Ecosystem Production (NEP) and Net Biome Production (NBP), depending on the boundary conditions (see Fig. 1 for each definition).

In order to calculate the net annual natural carbon sequestration capacity of global forest ecosystems, the IPCC Tier 1 method applied to the land-use category *Forest land remaining Forest land* of the Agriculture, Forestry and Other Land Use (AFOLU) is used in this paper (IPCC, 2006b).

According to the IPCC Gain-Loss Method (IPCC, 2006c), to account for the CO_2 fluxes between forest ecosystems and the atmosphere as net exchange in C stocks over time, Net Forest Production (NFP) requires the biomass carbon loss to be subtracted from the biomass carbon gain. Biomass carbon gain is represented by above and below-ground biomass growth, dead organic matter (assumed to have a net stock change equal to zero, so that no methods and parameters are provided according to Tier 1), and HWPs (harvested wood products), whereas carbon loss is represented by emissions due to soil respiration and forest wildfires (IPCC, 2006a). This calculation reflects the Net Ecosystem Production, and NFP is thus calculated as in Eq. (5):

$$\mathrm{NFP} = \left\{ \sum_{i,j,k} \left[A_{i,j,k} \times G_{\mathrm{W}_{i,j,k}} \times (1 + R_{i,j}) \right] - B_{\mathrm{W}} \right\} \times cf - S_{Rh} + \mathrm{HWPs} \tag{5}$$

where:

- A is the forested area by each domain i, and each ecological zone j, in each continent k, for each of the three considered forest classes (*primary*, *other regenerated* and/or *planted*), measured in hectares (ha). The sum of all the forested areas considered is equivalent to A_F in Eq. (4).
- G_W is the average annual above-ground biomass growth for the specific domain i, ecological zone j, and continent k, expressed in t d.m. $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$. G_W values vary with relation to natural forest and plantation (IPCC, 2006b, in Table 4.9 and Table 4.12, respectively).
- R is the ratio of below-ground biomass to above-ground biomass for a specific vegetation type; according to the IPCC method, the below ground growth is calculated as $(1 + R)$. R values are derived from IPCC (2006b, Table 4.4).
- B_w represents the tons of biomass (dry matter) annually lost in forest wildfires at the global level, approximately 0.33×10^9 t d.m. (Zhang et al., 2012). B_w is included in the calculation by subtracting it from the above- and below-ground biomass increased in forests as this burnt biomass does not represent an actual net carbon sequestration.
- cf is the carbon conversion factor to convert tons of dry matter[4] into tons of carbon (t C (t d.m.)$^{-1}$). The value used for above-ground forest biomass is 0.47 t C (t d.m.)$^{-1}$ (IPCC, 2006b). This is the default value for all types of trees and all climate domains (i.e. tropical, sub-tropical, temperate, boreal and polar).
- S_{Rh} is the amount of carbon lost, via heterotrophic respiration, by drained organic soils. It is expressed in t C yr^{-1} (see Eq. (6)).
- HWPs is the carbon gained in harvested wood products, expressed in t C yr^{-1}. HWPs are assumed to be biomass growth in one year and harvested in the same year but not burnt. It is included in the calculation by adding it to the above- and below-ground biomass increased in forests to estimate the total amount of biomass growth (and thus carbon sequestered) in that year.

According to Fahey et al. (2010), the most rapidly changing carbon pool is the aboveground live biomass (G_W), which can be accurately measured. However, the growth rate of biomass in forests strongly depends on the management regime, with noticeable differences between natural forests and plantations (IPCC, 2006b). As plantations are established for mainly human management practices and harvesting (IPCC, 2006b), they are made of relatively young stands and have a biomass growth rate higher than that of natural forests. As such, "above-ground net biomass growth in natural forests" (IPCC, 2006b, Table 4.9, page 4.57) have been here allocated to both *Primary* and *Other Naturally Regenerated* forest area. Whereas, "above-ground net biomass growth in Plantations" (IPCC, 2006b, Table 4.12, page 4.63) have been assigned to *Planted* forest area. Tables A1 and A2 in Appendix A provide raw data derived from IPCC and used as G_W values for *Natural* forests and *Plantations*.

Along with default IPCC values, additional biomass growth values have been calculated for *Plantations* by applying a Productivity Correction Factor. This is done to estimate the potential long term sequestration capacity of *Plantations* if this forest category were left un-managed and un-harvested. We have calculated the Productivity Correction Factor as the ratio between biomass growth occurring in *Natural* forests older than 20 years (>20 yr) and biomass growth in *Natural* forests younger than 20 years (<20 yr), using default values given by the IPCC (2006b; see also Table A1 in Appendix).

Soil respiration (S_{Rh}) is a major component of ecosystem-atmosphere CO_2 exchange, yet it remains a major challenge to estimate global average soil respiration for forests because of the high spatial variability in a number of controlling factors (Pan et al., 2011; Pregitzer and Euskirchen, 2004; Lal, 2005; Bond-Lamberty and Thomson, 2010; Randerson et al., 2002). Nevertheless, it is widely accepted that soil respiration is higher in young forests and naturally tends to decline during the later stages of succession (Luyssaert et al., 2008; Pregitzer and Euskirchen, 2004; Davidson et al., 2002; Petersen et al., 2013). Carbon emissions from soils are mostly due to land use and land use changes (Brandao et al., 2011) as well as agricultural activities (Lal, 2004) such as drainage and associated management activities (IPCC, 2006c).

Using the most updated datasets to our knowledge, this paper follows the IPCC Tier 1 method for estimating CO_2 emissions from soils and applies it to *Planted* forests, which are assumed to be

[4] Dry matter is related to the net annual increment (NAI) of biomass used to calculate the forest product Footprint component (Borucke et al., 2013), but they differ in the extent to which NAI does not account for the carbon released with autotrophic respiration.

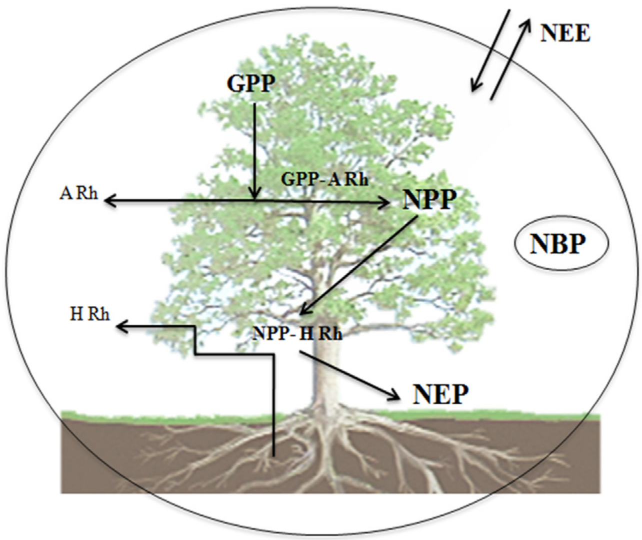

Fig. 1. Scheme of the carbon cycling in the forest biome. Nomenclature and definitions are consistent with IPCC (2006a).

relatively young and more exposed to human management practices (e.g. drainage). However, since a certain rate of soil respiration exists in each forest biome and age class (Pregitzer and Euskirchen, 2004), soil emissions have been also allocated to *Primary* and *Other Naturally Regenerated* forests. Although both organic and inorganic forms of carbon exists in soils, the Tier 1 method estimates only annual carbon flux generated from the organic layer and assigns an emission factor for each climate type (IPCC, 2006c). The amount of carbon loss from drained organic soils (S_{Rh}) is calculated as in Eq. (6) (directly from Eq. (2.26), IPCC, 2006c) and Table A5 in Appendix A provides emission factors values:

$$S_{Rh} = \sum_{c} (A \times EmFact)_c \tag{6}$$

where

- A is the land area of drained organic soils in climate c, (ha). Climate type area include Boreal (Boreal + Polar), Temperate and Tropical (Tropical + SubTropical).
- $EmFact$ is the emission factor for climate c, expressed in $\mathrm{t\,C\,ha^{-1}\,yr^{-1}}$ and derived from IPCC (IPCC, 2006b, Table 4.6).

In order to remain conservative with estimates of soil respiration in all forests, the lower values of emissions factors have been assigned to all three forest classes.

Forest wildfires (B_W) are major natural disturbances with both beneficial and detrimental effects on ecosystems (FAO, 2010). Wildfires release carbon into the atmosphere, alter hydrologic and ecologic environments, and affect terrestrial carbon sequestration, although such effects are partially offset or eliminated on decadal time scales through plant regrowth and ecosystem restoration (Zhang et al., 2012). Here we use a value of global biomass loss due to fires derived from Zhang et al. (2012), approximately 0.33×10^9 t d.m. per year.

Harvested wood products (HWPs) represent the storage of carbon in wood products and subsequent release as CO_2 at the end of the product's life cycle (IPCC, 2006d). Nevertheless, the harvested wood represents a fixed carbon storage assumed to last for the entire wood product's life (Pan et al., 2011). HWPs constitute a carbon reservoir and the time carbon is held in products varies depending on the product and its uses (IPCC, 2006d). IPCC guidelines and parameters (IPCC, 2006d) are used here to calculate the carbon stored in "products in use", that is the yearly harvested wood and its carbon content, which contributes annually to the carbon stock change in world forest. In particular, we accounted for annual change in carbon stock from paper and solid wood products, collecting data for the period 2000–2010 (FAOSTAT, 2014). The annual HWPs amount was found to be $8.41 \times 10^7\ \mathrm{t\,C\,yr^{-1}}$; dividing this by the total global forest area, the value is $0.02\ \mathrm{t\,C\,ha^{-1}\,yr^{-1}}$.

3. Results and discussion

Four calculation options have been set (and results are presented in Table 1) to account for the various parameters influencing the AFCS. Such calculation options primarily differ in the land classes they consider. *Primary* forests can be considered to act as actual sinks or not, depending on different ecological theories, whereas *Plantations* have different sequestration capacities depending on their standing life time. *Other naturally regenerated* forests are always assumed to be actual carbon sinks.

3.1. Choosing parameters: what to include or not to include?

3.1.1. Primary forest: classical theory vs. recent findings

According to the ecosystem development theory (Odum, 1969), *Primary* forests are considered ecosystems where plant growth slows and eventually reaches a steady state or decline over time. This perspective is shared by the IPCC (1996, p. 5.11) which states that "*Natural, unmanaged (for wood products) forests are not considered to be either an anthropogenic source or sink, and are excluded from the calculations*". Other studies (e.g., Field and Kaduk, 2004; Smith and Long, 2001) support this point of view, stating that an old growth forest ecosystem operates near the equilibrium, thus having a NEP close to zero, or is characterized by a decline in biomass production through time due to structural changes (i.e. development of canopy closure and maximum foliage). Following the theory that old forests lose much of their carbon sequestration capacity, calculation options 1 and 3 (see Table 1) exclude Primary forest from AFCS.

Nevertheless, recent studies have rejected this classical theory, arguing that old-growth forests might still sequester carbon (i.e., they have a positive NEP) thus acting as carbon sinks (Luyssaert et al., 2008; Hoover et al., 2012; Wayburn et al., 2007; Lal, 2005). According to Luyssaert et al. (2008), in an old-growth forest, many

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Table 1
Synoptic table showing different parameters in each calculation option and their resulting AFCS. Three different AFCS outcomes are provided to clarify how soil emissions, HWP and a combination of them influence the result. Only data presented in the last column have been chosen and discussed as they provide a complete framework of all the variables affecting forest's net ecosystem productivity (NEP).

	Primary forests	Other nat. regenerated forests	Planted forests	Soil emissions ($t\,C\,ha^{-1}\,yr^{-1}$)	AFCS		
					Excluding soil emissions ($t\,C\,ha^{-1}\,yr^{-1}$)	Including soil emissions ($t\,C\,ha^{-1}\,yr^{-1}$)	With soil and HWP ($t\,C\,ha^{-1}\,yr^{-1}$)
Biomass growth ($t\,d.m.\,yr^{-1}$)	4.00E+09	5.83E+09	2.21E+09				
Area (in ha)	1.36E+09	2.18E+09	2.64E+08				
Option 1	Excluded	Included	Included[a]	0.35	0.78	0.44	0.46
Option 2	Included	Included	Included[a]	0.56	1.27	0.71	0.73
Option 3	Excluded	Included	Included	0.35	0.94	0.60	0.62
Option 4	Included	Included	Included	0.56	1.43	0.87	0.89

[a] Production of planted forests reflects (<20) years old forest. To estimate biomass production for planted forests (>20) years, an average ratio of (<20) primary forest production to (>20) primary forest production is calculated. Production data for (<20) years planted forest is then multiplied by this factor.
Common parameters are:
– Global forest surface: 3.80E+09 ha.
– Forest fires: 3.35E+08 $t\,d.m.\,yr^{-1}$.
– HWP: 0.02 $t\,C\,ha^{-1}\,yr^{-1}$.

of the oldest trees are lost due to natural disturbance (i.e. lightning, insects, root instability in anchoring large stands, fungal attacks, etc.) and through the new recruitment of younger trees, thus maintaining productivity and accumulating carbon for centuries. Other studies provide positive mean values of NEP across all age classes and find that on average, total ecosystem carbon increase with age class in all climate zone, despite some variability due to the role of disturbances in regulating carbon cycling and storage, mostly in tropical forests (Pregitzer and Euskirchen, 2004; Pan et al., 2011). Accordingly, biomass growth in *Primary* forest has been included in calculation options 2 and 4 (see Table 1).

3.1.2. Planted forests: short-term management vs. long-term sequestration

Planted forests are defined by FAO (2010) as forests managed by human for two main purposes: production and protection. Production activities such as wood (industrial roundwood and woodfuel) and non-wood (food and fodder) products provision take place in approximately 75% of the plantation area (FAO, 2010). As such, planted forests are typically managed on relatively short-term rotation, every 15–20 years, resulting in recurring clear-cutting and biomass harvesting. To account for this, calculation options 3 and 4 use a higher value for biomass growth given by IPCC for Plantations (IPCC, 2006b. See also Table A3 in Appendix).

The category of *Planted* forests also includes protected forests, which may be left un-managed and un-harvested to grow and sequester carbon indefinitely. Based on this, calculation option 1 and 2 apply the Productivity Correction Factor to the biomass growth data provided for Plantation in IPCC (2006b) (see Section 2.1.2), thus accounting for the potential long term sequestration capacity of plantations.

3.2. A comparison with existing studies

According to the more recent findings that old-growth forests act as a significant carbon sink (Pan et al., 2011; Luyssaert et al., 2008; Stephenson et al., 2014; Schimel et al., 2014; Field and Kaduk, 2004), option 2 was deemed to be the calculation option most representative of the rationale behind the Ecological Footprint methodology. Additionally, option 2 includes *Planted* forest with the Productivity Correction Factor (see Section 2.1.2), and reflects the theoretical intent of the Footprint of quantifying world forests' long term carbon sequestration capacity.

Standard Deviation (St. Dev.) and the Standard Error of the Mean (SEM) were then calculated in line with Hozo et al. (2005) – by selecting minimum and maximum options in the raw data from IPCC regarding biomass growth in natural forests. The resulting world average forest carbon sequestration (AFCS) is estimated to be $0.73 \pm 0.37\,t\,C\,ha^{-1}\,yr^{-1}$ (see Table 2).

Results from this calculation option were thus compared with previous studies to determine the robustness of our calculations and understand the degree to which our result is consistent with data existing in the literature. For instance, Pan et al. (2011) performed a similar research on the total forest sink by using bottom-up estimates of carbon stock and fluxes in world forest ecosystems. They found the total sink capacity of global established forests (boreal, temperate and tropical intact forests) – the parameter closer to the forest's NEP investigate in this paper – to be $2.41 \pm 0.42\,Pg\,C\,yr^{-1}$, corresponding to $0.63 \pm 0.42\,t\,C\,ha^{-1}\,yr^{-1}$. The difference between this value and that of our study ($0.73 \pm 0.37\,t\,C\,ha^{-1}\,yr^{-1}$), is primarily due to the fact that biomass growth in "tropical re-growth" forests is excluded in Pan's "NEP-equivalent" calculation. Pan's study also provides a measure of the global net forest sink, amounting to $1.11 \pm 0.82\,Pg\,C\,yr^{-1}$. However, this value is not comparable to that of our analysis as it represents forests' Net Biome Production (NBP) rather than NEP (see also Fig. 1).

3.3. Implication of updated AFCS

The value of forests' carbon sequestration rate used in the 2014 Edition NFAs ($0.97\,t\,C\,ha^{-1}\,yr^{-1}$) is 33% higher than the AFCS result obtained in this paper ($0.73\,t\,C\,ha^{-1}\,yr^{-1}$) and within the upper limit of the SEM range calculated here. This difference is due to the use of updated and comprehensive data, an improved calculation methodology, as well as the inclusion of additional carbon pools (e.g., soil) to represent forests' Net Ecosystem Production.

According to the 2014 edition of the NFAs (Lazarus et al., 2014; WWF et al., 2014), per capita carbon Footprint in 2010 was 1.4 gha, representing 53% of the overall per capita Ecological Footprint (2.7 gha). Implementing the AFCS value obtained from calculation option 2 within the 2014 edition of the NFAs would result in an average per capita carbon Footprint of 1.9 gha and a range between 1.3 and 3.8 gha. The overall per capita Ecological Footprint would be 3.1 gha and ranging from 2.5 to 5.1 gha. Fig. 2 shows the effect of implementing the AFCS value of $0.73 \pm 0.37\,t\,C\,ha^{-1}\,yr^{-1}$

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Table 2
Different AFCS values depending on minimum, maximum and provided values selected from raw data in IPCC (IPCC, 2006a) regarding biomass growth in natural forests. The Standard Deviation (St. Dev.) and the Standard Error of the Mean (SEM) are also reported.

	AFCS Min $t\,C\,ha^{-1}\,yr^{-1}$	AFCS Max $t\,C\,ha^{-1}\,yr^{-1}$	AFCS Provided $t\,C\,ha^{-1}\,yr^{-1}$	St. Dev. $t\,C\,ha^{-1}\,yr^{-1}$	SEM $t\,C\,ha^{-1}\,yr^{-1}$
Option 2	0.14	1.42	0.73	0.64	0.37

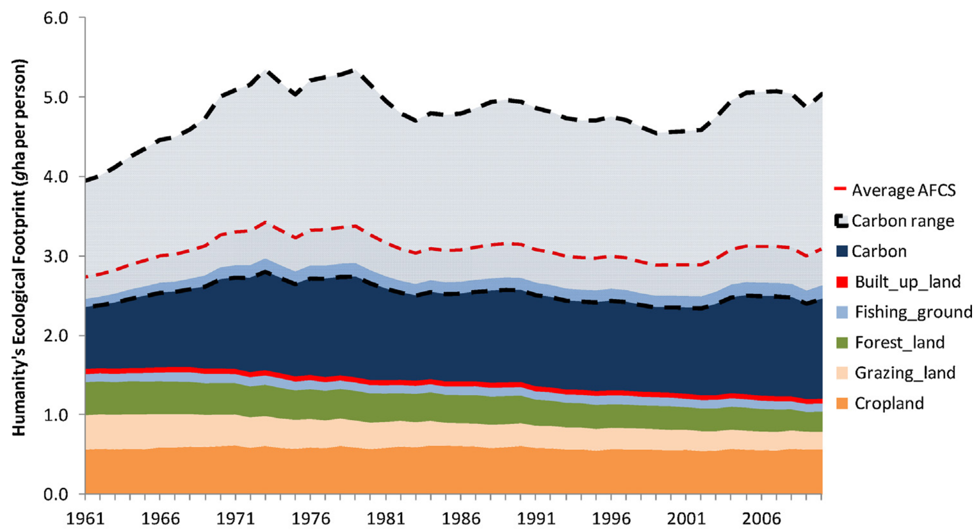

Fig. 2. Global Ecological Footprint by component, 1961–2010. Carbon Footprint is the largest component and its uncertainty range is shown according to the present study.

throughout the entire time period (1961–2010) covered by the NFAs: the carbon uncertainty area slightly overlaps, in its lower end, the carbon Footprint area as currently calculated in the 2014 edition of the NFAs. This means that the carbon Footprint value currently used in NFAs falls within the uncertainty range ensued from this study and, as it is close to the lower end of the range, it supports existing statements (Ewing et al., 2010) on the precautionary approach of the Ecological Footprint and its tendency to underestimate human pressure on the Earth's regenerative capacity.

4. Conclusion

Carbon Footprint represents the waste side of the Ecological Footprint methodology and accounts for the demand placed on the forest ecosystems' capacity to long-term sequester carbon dioxide emissions. This demand has become increasingly relevant in last decades, as the rapidly growing accumulation of carbon in the atmosphere is widely considered to be the prime driver of climate change. As such, this work revises and improves the calculations of a key parameter behind the carbon Footprint component: the average carbon sequestration capacity of a hectare of world average forest (AFCS).

This paper provided an accurate, accessible and reproducible dataset for AFCS calculation and assessed the likely sensitivity range to be applied to the result. Methods and most recent data about biomass growth provided by the IPCC and forest surface data from FAO were used. Thus, AFCS was obtained by accounting for (i) carbon gained by net dry matter growth in above ground (i.e. all the visible of the trees: trunk, branches and leaves) and below ground (i.e. roots) biomass, (ii) dry matter lost in wildfires (as subtraction from the biomass growth), (iii) carbon emissions due to soil respiration (thus as loss of carbon from the ecosystem), and (iv) carbon embedded in harvested wood products.

Results were presented in four calculation options to reflect the actual capacity of forests to sequester CO_2 depending on the degree of human management. The calculation option (number 2) which includes *Primary* forest as an active CO_2 sink, and *Planted* forests normalized to long-term sequestration capacity, was determined to most closely reflect the Ecological Footprint's theoretical intent to incorporate forests' long-term carbon sequestration capacity.

Replacing the previously-used AFCS value ($0.97\,t\,C\,ha^{-1}\,yr^{-1}$) with the value calculated here ($0.73\,t\,C\,ha^{-1}\,yr^{-1}$) in the calculation of the National Footprint Accounts 2014 edition caused the carbon Footprint and the total Ecological Footprint to increase by 33% and 17%, respectively in the year 2010. The difference is due to the use of more updated and comprehensive input data as well as to the fact that the new AFCS value represents a measure of forests' NEP (Net Ecosystem Production) rather than NPP (Net Primary Production). However, additional research is encouraged to further analyze the influence of other factors on the carbon Footprint as well on the overall Ecological Footprint (e.g., EQFs).

Finally, comparing the world Ecological Footprint and biocapacity results based on the four AFCS calculation options, it was found that humanity was overshooting the planet's regenerative capacity by 61–146% in 2010. Taking into account only the selected calculation option 2 and implementing the extreme values of its SEM range, humanity was found to overshoot the planet's regenerative capacity by 44–192% in 2010. These findings are in agreement with several other analyses indicating that societal metabolism is already operating beyond safe limits.

Acknowledgements

We would like to thank David Moore, Steve Goldfinger and Michela Marchi for their helpful and constructive comments. Acknowledgements are also due to Environment Agency – Abu Dhabi (EAD) and MAVA – Fondation pour la Protection de la Nature, for their support to Global Footprint Network's National Footprint Accounts Program.

Appendix A. Appendix A – Raw data tables

Tables A1–A5

Table A1
Above-ground Net Biomass Growth in natural forest.

Domain	Ecological zone	Continent	Min t d.m. ha^{-1} yr^{-1}	Max t d.m. ha^{-1} yr^{-1}	Provided t d.m. ha^{-1} yr^{-1}	Calculated average t d.m. ha^{-1} yr^{-1}
Tropical	Rain forest	Africa (≤20 yr)			10	
		Africa (>20 yr)			3.1	
		North America	0.9	18		9.45
		South America (≤20 yr)			11	
		South America (>20 yr)	1.5	5.6	3.1	
		Asia (continental ≤ 20 yr)	3	11	7	
		Asia (continental > 20 yr)	1.3	3	2.2	
		Asia (insular 20 yr)			13	
		Asia (insular > 20 yr)			3.4	
	Moist	Africa (≤20 yr)			5	
		Africa (>20 yr)			1.3	
		North America and south America (≤20 yr)			7	
		North America and south America (>20 yr)			2	
		Asia (continental ≤ 20 yr)			9	
		Asia (continental > 20 yr)			2	
		Asia (insular 20 yr)			11	
		Asia (insular > 20 yr)			3	
	Dry	Africa (≤20 yr)	2.3	2.5	2.4	
		Africa (>20 yr)	0.6	3	1.8	
		North America and south America (≤20 yr)			4	
		North America and south America (>20 yr)			1	
		Asia (continental ≤ 20 yr)			6	
		Asia (continental > 20 yr)			1.5	
		Asia (insular ≤ 20 yr)			7	
		Asia (insular > 20 yr)			2	
	Shrub	Africa (≤20 yr)	0.2	0.7		0.45
		Africa (>20 yr)	0.2	1.6	0.9	
		North America and south America (≤20 yr)			4	
		North America and south America (>20 yr)			1	
		Asia (continental ≤ 20 yr)			5	
		Asia (continental > 20 yr)	1.0	2.2	1.3	
		Asia (insular ≤ 20 yr)			2	
		Asia (insular 20 yr)			1	
	Desert					
	Mountain	Africa (≤20 yr)	2.0	5.0		3.5
		Africa (>20 yr)	1.0	1.5		1.3
		North America and south America (≤20 yr)	1.8	5		3.4
		North America and south America (>20 yr)	0.4	1.4		0.9
		Asia (continental ≤ 20 yr)	1.0	5.0		3.0
		Asia (continental > 20 yr)	0.5	1.0		0.8
		Asia (insular ≤ 20 yr)	3.0	12.0		7.5
		Asia (insular > 20 yr)	1.00	3.00		2.00
Sub-tropical	Humid	North America and south America (≤20 yr)			7	
		North America and south America (>20 yr)			2	
		Asia (continental ≤20 yr)			9	
		Asia (continental > 20 yr)			2	
		Asia (insular ≤ 20 yr)			11	
		Asia (insular > 20 yr)			3	
	Dry	Africa (≤20 yr)	2.3	2.5	2.4	
		Africa (>20 yr)	0.6	3	1.8	
		North America and south America (≤20 yr)			4	
		North America and south America (>20 yr)			1	
		Asia (continental ≤ 20 yr)			6	
		Asia (continental > 20 yr)			1.5	
		Asia (insular ≤ 20 yr)			7	
		Asia (insular > 20 yr)			2	
	Steppe	Africa (≤20 yr)	0.8	1.5	1.2	
		Africa (>20 yr)	0.2	1.6	0.9	
		North America and south America (≤20 yr)			4	
		North America and south America (>20 yr)			1	
		Asia (continental ≤ 20 yr)			5	
		Asia (continental > 20 yr)	1	2.2	1.3	
		Asia (insular ≤ 20 yr)			2	
		Asia (insular > 20 yr)			1	
	Desert				0	
	Mountain	Africa (≤20 yr)	2	5		3.5
		Africa (>20 yr)	1	5		3
		North America and south America (≤20 yr)	1.8	5		3.4
		North America and south America (>20 yr)	0.4	1.4		0.9
		Asia (continental ≤ 20 yr)	1	5		3
		Asia (continental > 20 yr)	0.5	1		0.75
		Asia (insular ≤20 yr)	3	12		7.5
		Asia (insular >20 yr)	1	3		2

Table A1 (*Continued*)

Domain	Ecological zone	Continent	Min t d.m. ha^{-1} yr^{-1}	Max t d.m. ha^{-1} yr^{-1}	Provided t d.m. ha^{-1} yr^{-1}	Calculated average t d.m. ha^{-1} yr^{-1}
Temperate		Europe			2.3	
	Oceanic	North America	1.2	105	15	
		New zeland	3.2	3.8	3.5	
		South America	2.4	8.9		5.65
		Asia (≤20 yr)	0.5	8	4	
		Europe (≤20 yr)	0.5	8	4	
	Continental	North America(≤20 yr)	0.5	8	4	
		Asia (>20 yr)	0.5	7.5	4	
		Europe (>20 yr)	0.5	7.5	4	
		North America (>20 yr)	0.5	7.5	4	
	Steppe					
	Desert					
		Asia	0.5	6	3	
	Mountain	Europe	0.5	6	3	
		North America	0.5	6	3	
Boreal		Asia	0.1	2.1		1.1
	Coniferous	Europe	0.1	2.1		1.1
		North America	0.1	2.1		1.1
		Asia	0.2	0.5	0.4	
	Tundra	Europe	0.2	0.5	0.4	
		North America	0.2	0.5	0.4	
		Asia (≤20 yr)	1	1.1		1.05
		Europe (≤20 yr)	1	1.1		1.05
	Mountain	North America (≤20 yr)	1	1.1		1.05
		Asia (>20 yr)	1.1	1.5		1.3
		Europe (>20 yr)	1	1.5		1.25
		North America (>20 yr)	1	1.5		1.25
POLAR	Polar					

Source: Adapted from Table 4.9 in IPCC (2006b). For calculating the AFCS, provided values were used. For instances in which only min and max range values were provided, an average value was calculated for use in the calculation.

Table A2
Above-ground Net Biomass Growth in forest plantation.

Domain	Ecological zone	t d.m. ha^{-1}yr^{-1}
Tropical	Rain forest	15.00
	Moist	10.00
	Dry	8.00
	Shrub	5.00
	Desert	
	Mountain	5.00
Sub-tropical	Humid	10.00
	Dry	8.00
	Steppe	5.00
	Desert	
	Mountain	5.00
Temperate	Oceanic	4.40
	Continental	4.00
	Steppe	
	Desert	
	Mountain	0.13
Boreal	Coniferous	1.00
	Tundra	0.40
	Mountain	1.00
Polar	Polar	

Source: Adapted from Table 4.12 in IPCC (2006b).

Table A3
Ratio of below-ground biomass to above-ground biomass (*R*).

Domain	Ecological zone	*R* [t root d.m. (t shoot d.m.)$^{-1}$]		
		Min	Max	Provided
Tropical	Rain forest			0.37
	Moist	0.22	0.33	0.24
	Dry	0.27	0.28	0.28
	Shrub			0.40
	Desert			
	Mountain	0.27	0.28	0.27
Sub-tropical	Humid	0.22	0.33	0.24
	Dry	0.27	0.28	0.28
	Steppe	0.26	0.71	0.32
	Desert			
	Mountain			
Temperate	Oceanic	0.12	0.49	0.20
	Continental	0.12	0.49	0.20
	Steppe			
	Desert			
	Mountain	0.12	0.49	0.20
Boreal	Coniferous	0.15	0.37	0.24
	Tundra	0.15	0.37	0.24
	Mountain	0.15	0.37	0.24
Polar	Polar			

Source: Adapted from Table 4.4 in IPCC (2006b).

Table A4
Area and biomass growth data for each domain, ecological zone, continent and class of forest.

Domain	Ecological zone	Continent	Primary forest			Other naturally regenerated forest			Planted forest		
			Area 1000 ha	Total biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}	Area 1000 ha	Total biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}	Area 1000 ha	Total biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}
Tropical	Rain forest	Africa	1.84E+04	4.25E+00	7.82E+04	1.68E+05	4.25E+00	7.13E+05	5.88E+03	2.06E+01	1.21E+05
		Asia	3.04E+04	3.84E+00	1.17E+05	9.94E+04	3.84E+00	3.81E+05	3.40E+04	2.06E+01	6.99E+05
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.06E+01	0.00E+00
		North and central America	1.24E+04	1.29E+01	1.60E+05	1.70E+04	1.29E+01	2.20E+05	1.71E+03	2.06E+01	3.51E+04
		Oceania	9.80E+03	3.84E+00	3.76E+04	4.18E+04	3.84E+00	1.60E+05	1.13E+03	2.06E+01	2.33E+04
		south America	3.86E+05	4.25E+00	1.64E+06	1.11E+05	4.25E+00	4.73E+05	8.55E+03	2.06E+01	1.76E+05
	Moist	Africa	1.16E+04	1.61E+00	1.87E+04	1.06E+05	1.61E+00	1.70E+05	3.70E+03	1.24E+01	4.59E+04
		Asia	9.26E+03	3.10E+00	2.87E+04	3.03E+04	3.10E+00	9.39E+04	1.04E+04	1.24E+01	1.29E+05
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+01	0.00E+00
		North and Central America	1.62E+04	2.48E+00	4.02E+04	2.23E+04	2.48E+00	5.53E+04	2.24E+03	1.24E+01	2.78E+04
		Oceania	4.59E+02	2.48E+00	1.14E+03	1.96E+03	2.48E+00	4.85E+03	5.30E+01	1.24E+01	6.57E+02
		South America	8.24E+04	2.48E+00	2.04E+05	2.38E+04	2.48E+00	5.90E+04	1.82E+03	1.24E+01	2.26E+04
	Dry	Africa	1.40E+04	2.30E+00	3.23E+04	1.28E+05	2.30E+00	2.95E+05	4.48E+03	1.02E+01	4.59E+04
		Asia	1.73E+04	2.24E+00	3.88E+04	5.66E+04	2.24E+00	1.27E+05	1.94E+04	1.02E+01	1.98E+05
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E+01	0.00E+00
		North and Central America	4.55E+03	1.28E+00	5.82E+03	6.26E+03	1.28E+00	8.02E+03	6.29E+02	1.02E+01	6.44E+03
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E+01	0.00E+00
		South America	1.02E+05	1.28E+00	1.31E+05	2.96E+04	1.28E+00	3.78E+04	2.27E+03	1.02E+01	2.32E+04
	Shrub	Africa	1.90E+03	1.26E+00	2.39E+03	1.73E+04	1.26E+00	2.18E+04	6.07E+02	7.00E+00	4.25E+03
		Asia	2.21E+03	1.61E+00	3.55E+03	7.22E+03	1.61E+00	1.16E+04	2.47E+03	7.00E+00	1.73E+04
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.00E+00	0.00E+00
		North and Central America	0.00E+00	1.40E+00	0.00E+00	0.00E+00	1.40E+00	0.00E+00	0.00E+00	7.00E+00	0.00E+00
		Oceania	4.97E+03	1.26E+00	6.26E+03	2.12E+04	1.26E+00	2.67E+04	5.74E+02	7.00E+00	4.02E+03
		South America	9.16E+02	1.40E+00	1.28E+03	2.64E+02	1.40E+00	3.70E+02	2.03E+01	7.00E+00	1.42E+02
	Desert	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Asia	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		North and Central America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		South America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Mountain	Africa	1.28E+03	1.59E+00	2.03E+03	1.16E+04	1.59E+00	1.85E+04	4.08E+02	6.35E+00	2.59E+03
		Asia	7.39E+03	1.75E+00	1.29E+04	2.41E+04	1.75E+00	4.22E+04	8.27E+03	6.35E+00	5.25E+04
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.35E+00	0.00E+00
		North and Central America	7.60E+03	1.14E+00	8.69E+03	1.05E+04	1.14E+00	1.20E+04	1.05E+03	6.35E+00	6.67E+03
		Oceania	1.05E+03	1.14E+00	1.20E+03	4.48E+03	1.14E+00	5.12E+03	1.21E+02	6.35E+00	7.71E+02
		South America	3.08E+04	1.14E+00	3.52E+04	8.89E+03	1.14E+00	1.02E+04	6.82E+02	6.35E+00	4.33E+03
Sub-tropical	Humid	Africa	1.01E+02	2.48E+00	2.51E+02	9.22E+02	2.48E+00	2.29E+03	3.23E+01	1.24E+01	4.01E+02
		Asia	1.37E+04	3.10E+00	4.24E+04	4.47E+04	3.10E+00	1.38E+05	1.53E+04	1.24E+01	1.90E+05
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+01	0.00E+00
		North and Central America	2.19E+04	2.48E+00	5.44E+04	3.02E+04	2.48E+00	7.48E+04	3.03E+03	1.24E+01	3.76E+04
		Oceania	3.06E+03	2.48E+00	7.58E+03	1.30E+04	2.48E+00	3.23E+04	3.53E+02	1.24E+01	4.38E+03
		South America	7.61E+03	2.48E+00	1.89E+04	2.20E+03	2.48E+00	5.45E+03	1.68E+02	1.24E+01	2.09E+03

Table A4 (*Continued*)

Domain	Ecological zone	Continent	Primary forest			Other naturally regenerated forest			Planted forest		
			Area 1000 ha	Total biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}	Area 1000 ha	Total biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}	Area 1000 ha	Total biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}
Sub-tropical	Dry	Africa	5.25E+02	2.30E+00	1.21E+03	4.79E+03	2.30E+00	1.10E+04	1.68E+02	1.02E+01	1.72E+03
		Asia	8.06E+02	2.24E+00	1.81E+03	2.64E+03	2.24E+00	5.91E+03	9.03E+02	1.02E+01	9.24E+03
		Europe	1.03E+04	2.30E+00	2.38E+04	2.64E+04	2.30E+00	6.09E+04	2.74E+03	1.02E+01	2.80E+04
		North and Central America	9.31E+02	1.28E+00	1.19E+03	1.28E+03	1.28E+00	1.64E+03	1.29E+02	1.02E+01	1.32E+03
		Oceania	2.06E+03	2.30E+00	4.76E+03	8.80E+03	2.30E+00	2.03E+04	2.38E+02	1.02E+01	2.44E+03
		South America	6.27E+03	1.28E+00	8.02E+03	1.81E+03	1.28E+00	2.32E+03	1.39E+02	1.02E+01	1.42E+03
	Steppe	Africa	0.00E+00	1.19E+00	0.00E+00	0.00E+00	1.19E+00	0.00E+00	0.00E+00	6.60E+00	0.00E+00
		Asia	4.23E+02	1.52E+00	6.43E+02	1.38E+03	1.52E+00	2.10E+03	4.74E+02	6.60E+00	3.13E+03
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.60E+00	0.00E+00
		North and Central America	4.17E+03	1.32E+00	5.51E+03	5.74E+03	1.32E+00	7.58E+03	5.77E+02	6.60E+00	3.81E+03
		Oceania	8.83E+03	1.32E+00	1.17E+04	3.76E+04	1.32E+00	4.97E+04	1.02E+03	6.60E+00	6.73E+03
		South America	4.51E+02	1.32E+00	5.95E+02	1.30E+02	1.32E+00	1.72E+02	9.98E+00	6.60E+00	6.59E+01
	Desert	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Asia	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		North and Central America	2.43E+03	0.00E+00	0.00E+00	3.34E+03	0.00E+00	0.00E+00	3.36E+02	0.00E+00	0.00E+00
		Oceania	1.14E+03	0.00E+00	0.00E+00	4.84E+03	0.00E+00	0.00E+00	1.31E+02	0.00E+00	0.00E+00
		South America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Mountain	Africa	1.33E+02	1.25E+00	1.66E+02	1.21E+03	1.25E+00	1.51E+03	4.24E+01	5.00E+00	2.12E+02
		Asia	1.02E+04	1.38E+00	1.41E+04	3.35E+04	1.38E+00	4.61E+04	1.15E+04	5.00E+00	5.73E+04
		Europe	1.46E+03	1.25E+00	1.83E+03	3.74E+03	1.25E+00	4.67E+03	3.87E+02	5.00E+00	1.94E+03
		North and Central America	1.62E+04	9.00E−01	1.46E+04	2.23E+04	9.00E−01	2.00E+04	2.24E+03	5.00E+00	1.12E+04
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.00E+00	0.00E+00
		South America	6.76E+02	9.00E−01	6.09E+02	1.95E+02	9.00E−01	1.76E+02	1.50E+01	5.00E+00	7.49E+01
Temperate	Oceanic	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.28E+00	0.00E+00
		Asia	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.28E+00	0.00E+00
		Europe	7.34E+03	2.76E+00	2.03E+04	1.88E+04	2.76E+00	5.18E+04	1.94E+03	5.28E+00	1.03E+04
		North and Central America	7.01E+02	1.80E+01	1.26E+04	9.65E+02	1.80E+01	1.74E+04	9.70E+01	5.28E+00	5.12E+02
		Oceania	2.16E+03	4.20E+00	9.08E+03	9.22E+03	4.20E+00	3.87E+04	2.50E+02	5.28E+00	1.32E+03
		South America	5.31E+03	6.78E+00	3.60E+04	1.53E+03	6.78E+00	1.04E+04	1.18E+02	5.28E+00	6.21E+02
	Continental	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.80E+00	0.00E+00
		Asia	7.35E+03	4.80E+00	3.53E+04	2.40E+04	4.80E+00	1.15E+05	8.23E+03	4.80E+00	3.95E+04
		Europe	3.33E+04	4.80E+00	1.60E+05	8.52E+04	4.80E+00	4.09E+05	8.82E+03	4.80E+00	4.23E+04
		North and Central America	3.44E+04	4.80E+00	1.65E+05	4.73E+04	4.80E+00	2.27E+05	4.75E+03	4.80E+00	2.28E+04
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.80E+00	0.00E+00
		South America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.80E+00	0.00E+00
	Steppe	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Asia	1.92E+03	0.00E+00	0.00E+00	6.26E+03	0.00E+00	0.00E+00	2.14E+03	0.00E+00	0.00E+00
		Europe	2.51E+03	0.00E+00	0.00E+00	6.40E+03	0.00E+00	0.00E+00	6.63E+02	0.00E+00	0.00E+00
		North and Central America	1.90E+03	0.00E+00	0.00E+00	2.61E+03	0.00E+00	0.00E+00	2.62E+02	0.00E+00	0.00E+00
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		South America	3.52E+02	0.00E+00	0.00E+00	1.02E+02	0.00E+00	0.00E+00	7.80E+00	0.00E+00	0.00E+00

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Table A4 (*Continued*)

Domain	Ecological zone	Continent	Primary forest			Other naturally regenerated forest			Planted forest		
			Area 1000 ha	Above-ground biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}	Area 1000 ha	Above-ground biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}	Area 1000 ha	Above-ground biomass yield t d.m. ha^{-1} yr^{-1}	Total biomass growth 1000 t d.m. yr^{-1}
Temperate	Desert	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Asia	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Europe	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		North and Central America	2.70E+03	0.00E+00	0.00E+00	3.71E+03	0.00E+00	0.00E+00	3.73E+02	0.00E+00	0.00E+00
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		South America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Mountain	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.50E−01	0.00E+00
		Asia	6.10E+03	3.60E+00	2.20E+04	1.99E+04	3.60E+00	7.18E+04	6.83E+03	1.50E−01	1.02E+03
		Europe	1.50E+04	3.60E+00	5.39E+04	3.82E+04	3.60E+00	1.38E+05	3.96E+03	1.50E−01	5.94E+02
		North and Central America	4.16E+04	3.60E+00	1.50E+05	5.73E+04	3.60E+00	2.06E+05	5.75E+03	1.50E−01	8.63E+02
		Oceania	1.97E+03	3.60E+00	7.08E+03	8.38E+03	3.60E+00	3.02E+04	2.27E+02	1.50E−01	3.41E+01
		South America	1.13E+03	3.60E+00	4.06E+03	3.25E+02	3.60E+00	1.17E+03	2.50E+01	1.50E−01	3.74E+00
Boreal	Coniferous	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+00	0.00E+00
		Asia	2.48E+03	1.36E+00	3.38E+03	8.11E+03	1.36E+00	1.11E+04	2.78E+03	1.24E+00	3.44E+03
		Europe	1.14E+05	1.36E+00	1.55E+05	2.91E+05	1.36E+00	3.96E+05	3.01E+04	1.24E+00	3.73E+04
		North and Central America	5.26E+04	1.36E+00	7.18E+04	7.24E+04	1.36E+00	9.88E+04	7.27E+03	1.24E+00	9.02E+03
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+00	0.00E+00
		South America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+00	0.00E+00
	Tundra	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.96E−01	0.00E+00
		Asia	0.00E+00	4.96E−01	0.00E+00	0.00E+00	4.96E−01	0.00E+00	0.00E+00	4.96E−01	0.00E+00
		Europe	6.88E+03	4.96E−01	3.41E+03	1.76E+04	4.96E−01	8.72E+03	1.82E+03	4.96E−01	9.03E+02
		North and Central America	3.71E+04	4.96E−01	1.84E+04	5.10E+04	4.96E−01	2.53E+04	5.12E+03	4.96E−01	2.54E+03
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.96E−01	0.00E+00
		South America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.96E−01	0.00E+00
	Mountain	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+00	0.00E+00
		Asia	1.39E+02	1.61E+00	2.24E+02	4.53E+02	1.61E+00	7.31E+02	1.55E+02	1.24E+00	1.92E+02
		Europe	6.98E+04	2.23E+00	1.56E+05	1.78E+05	2.23E+00	3.98E+05	1.85E+04	1.24E+00	2.29E+04
		North and Central America	1.91E+04	2.85E+00	5.45E+04	2.63E+04	2.85E+00	7.50E+04	2.64E+03	1.24E+00	3.27E+03
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+00	0.00E+00
		South America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+00	0.00E+00
Polar	Polar	Africa	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Asia	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		Europe	1.59E+03	0.00E+00	0.00E+00	4.05E+03	0.00E+00	0.00E+00	4.20E+02	0.00E+00	0.00E+00
		North and Central America	3.22E+03	0.00E+00	0.00E+00	4.43E+03	0.00E+00	0.00E+00	4.45E+02	0.00E+00	0.00E+00
		Oceania	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
		South America	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A5
Emission factors for drained organic soils in managed forests.

Climate	Min $t\,C\,ha^{-1}\,yr^{-1}$	Max $t\,C\,ha^{-1}\,yr^{-1}$	Values $t\,C\,ha^{-1}\,yr^{-1}$
Tropical	0.82	3.82	1.36
Temperate	0.41	1.91	0.68
Boreal	0.08	1.09	0.16

Source: Adapted from Table 4.6 in IPCC (2006b).

References

Ayres, R.U., 2000. Commentary on the utility of the Ecological Footprint concept. Ecol. Econ. 32 (3), 347–349.

Barnosky, A.D., Hadley, E.A., Bascompte, J., Berlow, E.L., Brown, J.H., Fortelius, M., Getz, W.M., Harte, J., Hastings, A., Marquet, P.A., Martinez, N.D., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J.W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D.P., Revilla, E., Smith, A.B., 2012. Approaching a state shift in Earth's biosphere. Nature 486, 52–58.

Bauler, T., 2012. An analytical framework to discuss the usability of (environmental) indicators for policy. Ecol. Indic. 17, 38–45.

Blomqvist, L., Brook, B.W., Ellis, E.C., Kareiva, P.M., Nordhaus, T., Shellenberger, M., 2013. Does the shoe fit? Real versus imagined ecological footprints. PLoS Biol. 11, e1001700.

Bond-Lamberty, B., Thomson, A., 2010. A global database of soil respiration data. Biogeoscience 7, 1915–1926.

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

Bradshaw, C.J.A., Brook, B.W., 2014. Human population reduction is not a quick fix for environmental problems. Proc. Natl. Acad. Sci. U. S. A. 111 (46), 16610–16615.

Brandão, M., Milaì Canals, L., Clift, R., 2011. Soil organic carbon changes in the cultivation of energy crops: Implications for GHG balances and soil quality for use in LCA. Biomass Bioenergy 35, 2323–2336.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Morcillo, M.H., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.-C., Watson, R., 2010. Global biodiversity: indicators of recent declines. Science 328, 1164, http://dx.doi.org/10.1126/science.1187512.

Crutzen, P.J., 2002. Geology of mankind: the anthropocene. Nature 415, 23, http://dx.doi.org/10.1038/415023a.

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

Davidson, E.A., Savage, K., Bolstad, P., Clark, D.A., Curtis, P.S., Ellsworth, D.S., Hanson, P.J., Law, B.E., Luo, Y., Pregitzer, K.S., Randolph, J.C., Zak, D., 2002. Belowground carbon allocation in forests estimated from litterfall and IRGA-based soil respiration measurements. Agric. Forest Meteorol. 113, 39–51.

Ehrlich, P.R., 1982. Human carrying capacity, extinction and nature reserves. Bioscience 32 (5), 331–333.

Ellis, E.C., Goldewijk, K.G., Siebert, S., Lightman, D., Ramankutty, N., 2010. Anthropogenic transformation of the biomes, 1700 to 2000. Global Ecol. Biogeogr. 19, 589–606.

EPLCA, 2007. Carbon Footprint—What it is and How to Measure it. European Platform on Life Cycle Assessment. European Commission.

Ewing, B., Moore, D., Goldfinger, S., Oursler, A., Reed, A., Wackernagel, M., 2010. The Ecological Footprint Atlas 2010. Global Footprint Network, Oakland www.footprintnetwork.org/atlas.

Fahey, T.J., Woodbury, P.B., Battles, J.J., Goodale, C.L., Hamburg, S., Ollinger, S., Woodall, C.W., 2010. Forest carbon storage: ecology, management, and policy. Frontiers in Ecology and the Environment, 8. Ecological Society of America, pp. 245–252.

FAO, 2000. Global Forest Report Assessment 2000, main report.

FAO, 2010. Global Forest Report Assessment 2010, main report.

FAOSTAT, 2014. FAO website, Available from: http://faostat3.fao.org/faostat-gateway/go/to/download/F/FO/E [Accessed September 2014].

FAO and IIASA (International Institute for Applied Systems Analysis), 2000. Global Agro-Ecological Zones, http://www.fao.org/ag/agl/agll/gaez/index.htm (accessed February 2011).

Field, C.B., Kaduk, J., 2004. The carbon balance of an old-growth forest: building across approaches. Ecosystems 7, 525–533, http://dx.doi.org/10.1007/s10021-004-0142-7.

Galli, A., Kitzes, J., Wermer, P., Wackernagel, M., Niccolucci, V., Tiezzi, E., 2007. An exploration of the mathematics behind the Ecological Footprint. Int. J. Ecodyn. 2 (4), 250–257.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2012. Integrating ecological, carbon and water footprint into a "Footprint Family" of indicators: definition and role in tracking human pressure on the planet. Ecol. Indic. 16, 100–112.

Galli, A., Wackernagel, M., Iha, K., Lazarus, E., 2014. Ecological Footprint: implications for biodiversity. Biol. Conserv. 173, 121–132.

Galli, A., 2015. On the rationale and policy usefulness of ecological footprint accounting: the case of Morocco. Environ. Sci. Policy 48, 210–224.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge.

Giampietro, M., Saltelli, A., 2014. Footprints to nowhere. Ecol. Indic., http://dx.doi.org/10.1016/j.ecolind.2014.01.030.

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

Hoover, C.M., Leak, W.B., Keel, B.G., 2012. Benchmark carbon stocks from old-growth forests in northern New England, USA. Forest Ecol. Manage. 266, 108–114.

Hozo, S.P., Djulbegovic, B., Hozo, I., 2005. Estimating the mean and variance from the median, range, and the size of a sample. BMC Med. Res. Methodol. 5, 13, http://dx.doi.org/10.1186/1471-2288-5-13.

IEA, 2010. CO_2 Emissions from Fuel Combustion Database.

1996. Land-Use Change and Forestry. In: Revised Guidelines for National Greenhouse Gas Inventories. Volume 3: Reference Manual. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (Chapter 5).

IPCC, 2006a. Introduction. In: Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (Chapter 1).

IPCC, 2006b. Forest land. In: Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (Chapter 4).

IPCC, 2006c. Generic methodologies applicable to multiple land-use categories. In: Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (Chapter 2).

IPCC, 2006d. Harvested Wood Products. In: Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (Chapter 12).

Khatiwala, S., Primeau, F., Hall, T., 2009. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. Nature 462, 346–350.

Kitzes, J., Galli, A., Bagliani, M., Barrett, J., Dige, G., Ede, S., Erb, K., Giljum, S., Haberl, H., Hails, C., Jolia-Ferrier, L., Jungwirth, S., Lenzen, M., Lewis, K., Loh, J., Marchettini, N., Messinger, H., Milne, K., Wada, Y., Walsh, C., Wiedmann, T., 2009. A research agenda for improving national Ecological Footprint accounts. Ecol. Econ. 68, 1991–2007.

Kitzes, J., Wackernagel, M., Loh, J., Peller, A., Goldfinger, S., Cheng, D., Tea, K., 2008a. Shrink and share: humanity's present and future Ecological Footprint. Philos. Trans. R. Soc. B: Biol. Sci. 363, 467–475.

Kitzes, J., Galli, A., Rizk, S.M., Reed, A., Wackernagel, M., 2008b. Guidebook to the National Footprint Accounts: 2008 Edition. Global Footprint Network, Oakland.

Kitzes, J., Wackernagel, M., 2009. Answer to common questions in Ecological Footprint accounting. Ecol. Indic. 9, 812–817.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123, 1–22.

Lal, R., 2005. Forest soils and carbon sequestration. Forest Ecol. Manage. 220, 242–258.

Lazarus, E., Zokai, G., Borucke, M., Panda, D., Iha, K., Morales, J.C., Wackernagel, M., Galli, A., Gupta, N., 2014. Working Guidebook to the National Footprint Accounts: 2014 Edition. Global Footprint Network, Oakland.

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A., 2012. International trade drives biodiversity threats in developing nations. Nature 486, 109–112.

LPR, 2012. WWF (WWF International), Global Footprint Network, ZSL (Zoological Society of London), 2012. Living Planet Report 2012. WWF, Gland, Switzerland, Available from: http://wwf.panda.org/about_our_earth/all_publications/living_planet_report/2012_lpr/.

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215.

Mancini, M.S., (Master's thesis) 2012. The role of carbon dioxide in ecological footprint accounting. University of Siena, Siena.

Max-Neef, M., 1995. Economic growth and quality of life: a threshold hypothesis. Ecol. Econ. 15, 115–118.

MEA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W., 1972. The Limits to Growth. Universe Books, New York.

Moldan, B., Janousková, S., Hák, T., 2012. How to understand and measure environmental sustainability: indicators and targets. Ecol. Indic. 17, 4–13.

Monfreda, C., Wackernagel, M., Deumling, D., 2004. Establishing national natural capital accounts based on detailed Ecological Footprint and biological capacity assessments. Land Use Policy 21, 231–246.

Neumayer, E., 2013. Weak Versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms, 4th ed. Edward Elgar, Cheltenham, UK and Northampton, MA.

Niccolucci, V., Galli, A., Kitzes, J., Pulselli, R.M., Borsa, S., Marchettini, N., 2008. Ecological Footprint analysis applied to the production of two Italian wines. Agric. Ecosyst. Environ. 128, 162–166.

Niccolucci, V., Pulselli, F.M., Tiezzi, E., 2007. Strengthening the threshold hypothesis: economic and biophysical limits to growth. Ecol. Econ. 60, 667–672.

Niccolucci, V., Tiezzi, E., Pulselli, F.M., Capineri, C., 2012. Biocapacity vs Ecological Footprint of world regions: a geopolitical interpretation. Ecol. Indic. 16, 23–30.

Odum, E.P., 1969. The strategy of ecosystem development. Science 164 (3877), 262–270.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science, 333, http://dx.doi.org/10.1126/science.1201609.

Petersen, B.M., Knudsen, M.T., Hermansen, J.E., Halberg, N., 2013. An approach to include soil carbon changes in life cycle assessments. J. Cleaner Prod. 52, 217–224.

Pregitzer, K.S., Euskirchen, E.S., 2004. Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biol. 10, 2052–2077.

Pulselli, F.M., Bastianoni, S., Marchettini, N., Tiezzi, E., 2008. The Road to Sustainability. GDP and Future Generation. WIT Press, Great Britain.

Randerson, J.T., Chapin, F.S., Harden, J.W., Neff, J.C., Harmon, M.E., 2002. Net ecosystem production: a comprehensive measure of net carbon accumulation by ecosystems. Ecol. Appl. 12 (4), 937–942.

Rockström, R., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Science 46, 472–475.

Schimel, D., Stephens, B.B., Fisher, J.B., 2014. Effect of increasing CO_2 on the terrestrial carbon cycle. Proc. Natl. Acad. Sci. U. S. A. 112 (2), 436–441.

Smith, F.W., Long, J.N., 2001. Age-related decline in forest growth: an emergent property. Forest Ecol. Manage. 144, 175–181.

Steffen, W., Crutzen, P.J., McNeil, J.R., 2007. The anthropocene: are humans now overwhelming the great forces of nature? Ambio 36, 614–621.

Stephenson, N.L., Das, A.J., Condit, R., Russo, S.E., Baker, P.J., Beckman, N.G., Zavala, M.A., 2014. Rate of tree carbon accumulation increases continuously with tree size. Nature 507 (7490), 90–93.

Tiezzi, E., 1984. Tempi Storici, Tempi Biologici. Garzanti, Milano, pp. 1984.

Van den Bergh, J.C.J.M., Grazi, F., 2013. Ecological Footprint policy? Land use as an environmental indicator. J. Ind. Ecol. 18 (1).

Van den Bergh, J.C.J.M., Verbruggen, H., 1999. Spatial sustainability, trade and indicators: an evaluation of the "ecological footprint". Ecol. Econ. 29, 61–72.

Wackernagel, M., (Ph.D. thesis) 1994. Ecological Footprint and appropriated carrying capacity: a tool for planning toward sustainability. School of Community and Regional Planning, The University of British Columbia.

Wackernagel, M., Onisto, L., Bello, P., Callejas Linares, A., LópezFalfán, I.S., García, J.M., Suárez Guerrero, A.I., Suárez Guerrero, M.G., 1999. National natural capital accounting with the ecological footprint concept. Ecol. Econ. 29, 375–390.

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

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

Wackernagel, M., Silverstein, J., 2000. Big things first: focusing on the scale imperative with the ecological footprint. Ecol. Econ. 32 (3), 391–394.

Wayburn, L.A., Franklin, J.F., Gordon, J.C., Binkley, C.S., Mladenoff, D.J., Christensen Jr., N.L., 2007. Forest Carbon in the United States: Opportunities & Option for Private Lands. The Pacific Forest Trust 2000, www.pacificforest.org.

Wiedmann, T., Barrett, J., 2010. A review of the Ecological Footprint indicator—perceptions and methods. Sustainability 2, 1645–1693.

Wiedmann, T., Minx, J., 2008. A definition of 'Carbon Footprint'. In: Ecological Economics Research Trends. NovaScience Publishers, Hauppauge, NY, pp. 1–11 (Chapter 1).

World Conservation Union, United Nations Environment Programme, World Wide Fund for Nature, 1991. Caring for the Earth: A Strategy for Sustainable Living. World Conservation Union, Gland, Switzerland.

WWF (WWF International), ZSL (Zoological Society of London), Global Footprint Network, Water Footprint Network, 2014. Living Planet Report 2014. WWF, Gland, Switzerland, ISBN 978-2-940443-87-1. Available from: http://wwf.panda.org/about_our_earth/all_publications/living_planet_report/.

Zhang, X., Kondragunta, S., Ram, J., Smhmidt, C., Huang, H.-C, 2012. Near-real-time global biomass burning emissions product from geostationary satellite constellation. J. Geophys. Res. D: Atmos. 117 (14).

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