Accounting for demand and supply of the Biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework

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ABSTRACT

Human demand on ecosystem services continues to increase, and evidence suggests that this demand is outpacing the regenerative and absorptive capacity of the biosphere. As a result, the productivity of natural capital may increasingly become a limiting factor for the human endeavor. Therefore, metrics tracking human demand on, and availability of, regenerative and waste absorptive capacity within the biosphere are needed. Ecological Footprint analysis is such a metric; it measures human appropriation (Ecological Footprint) and biosphere's supply (biocapacity) of ecosystem products and services in terms of the amount of bioproductive land and sea area needed to supply these products and services.

This paper documents the latest method for estimating the Ecological Footprint and biocapacity of nations, using the National Footprint Accounts (NFA) applied to more than 200 countries and for the world overall. Ecological Footprint and biocapacity calculation covers six land use types: cropland, grazing land, fishing ground forest land, built-up land, and the uptake land to accommodate the carbon Footprint. For each land use type, the demand for ecological products and services is divided by the respective yield to arrive at the Footprint of each land use type. Ecological Footprint and biocapacity are scaled with yield factors and equivalence factors to convert this physical land demanded into world average biologically productive land, expressed in global hectares (gha). This measurement unit allows for comparisons between various land use types with differing productivities. According to the 2011 Edition of the National Footprint Accounts, humanity demanded the resources and services of 1.5 planets in 2008; this human demand to planet ratio has increased 2.5 times since 1961.

Situations in which total demand for ecological goods and services exceed the available supply for a given location, are called 'overshoot'. 'Global overshoot' indicates that stocks of ecological capital are depleting and/or that waste is accumulating.

Keywords: Ecological Footprint, biocapacity, method, resource accounting, Overshoot.

1. Introduction

Humanity relies on life-supporting ecosystem products and services including resources, waste absorptive capacity, and space to host urban infrastructure. Environmental changes such as deforestation, collapsing fisheries, and carbon dioxide (CO_2) accumulation in the atmosphere indicate that human demand is likely to be exceeding the regenerative and absorptive capacity of the biosphere. Careful management of human interaction with the biosphere is essential to ensure future prosperity; and reliable accounting systems are thus needed for tracking the regenerative and waste absorptive capacity of the biosphere. Assessing current ecological supply and demand as well as historical trends provides a basis for setting goals, identifying options for action, and tracking progress toward stated goals. The National Footprint Accounts (NFA) presented here aim to provide such an accounting system in a way that may be applied consistently across countries as well as over time. This paper describes the methodology followed for the calculation of the 2011 National Footprint Accounts reaching from 1961 to 2008.

The first systematic attempt to calculate the Ecological Footprint and biocapacity of nations began in 1997 (Wackernagel et al. 1997). Building on these assessments, Global Footprint Network initiated its National Footprint Accounts (NFA) program in 2003, with the most recent Edition issued in 2011.

The National Footprint Accounts constitute an accounting framework quantifying the annual supply of, and demand for, key ecosystem services by means of two measures (Wackernagel et al., 2002):

- The ***Ecological Footprint*** is a measure of the demand that populations and activities place on the biosphere in a given year - with prevailing technology and resource management of that year.
- The ***biocapacity*** is a measure of the amount of biologically productive land and sea area available to provide the ecosystem services that humanity consumes – our ecological budget or nature's regenerative capacity.

Ecological Footprint and biocapacity values are expressed in mutually exclusive units of area necessary to annually provide (or regenerate) such ecosystem services: cropland for the provision of plant-based food and fiber products; grazing land and cropland for animal products; fishing grounds (marine and inland) for fish products; forests for timber and other forest products; uptake land to accommodate for the absorption of anthropogenic carbon dioxide emissions (carbon Footprint); and built-up areas for shelter and other infrastructure.

The National Footprint Accounts measure one main aspect of sustainability only - *how much biocapacity humans demand, and how much is available* - not all aspects of sustainability, nor all environmental concerns. The attempt to answer this particular scientific research question is motivated by the assumption that the Earth's regenerative capacity is the limiting factor for the human economy in times when human demand exceeds what the biosphere can renew.

This paper describes the methodology for calculating the Ecological Footprint and biocapacity utilized in the 2011 Edition of the National Footprint Accounts and provides researchers and practitioners with information to deepen their understanding of the calculation methodology. It builds on previous Ecological Footprint work and methodology papers for the National Footprint Accounts (Rees 1992, Wackernagel, 1994; Wackernagel and Rees, 1996; Wackernagel et al. 1997, Wackernagel et al. 1999a, b, Wackernagel et al. 2002, Monfreda et al. 2004, Wackernagel et al. 2005, Galli, 2007; Kitzes et al. 2007a, Ewing et al. 2010a).

2. Fundamental assumptions of Ecological Footprint accounting

Ecological Footprint accounting is based on six fundamental assumptions (adapted from Wackernagel et al. 2002):

- The majority of the resources people consume and the wastes they generate can be quantified and tracked.
- An important subset of these resource and waste flows can be measured in terms of the biologically productive area necessary to maintain them. Resource and waste flows that cannot be measured are excluded from the assessment, leading to a systematic underestimate of humanity's true Ecological Footprint.
- By weighting each area in proportion to its bioproductivity, different types of areas can be converted into the common unit of global hectares, hectares with world average bioproductivity.
- Because a single global hectare represents a single use, and each global hectare in any given year represents the same amount of bioproductivity, they can be added up to obtain an aggregate indicator of Ecological Footprint or biocapacity.
- Human demand, expressed as the Ecological Footprint, can be directly compared to nature's supply, biocapacity, when both are expressed in global hectares.
- Area demanded can exceed area supplied if demand on an ecosystem exceeds that ecosystem's regenerative capacity.

3. National Footprint Accounts: data sources and accounting framework

The 2011 Edition of the National Footprint Accounts (NFA) calculate the Ecological Footprint and biocapacity of more than 200 countries and territories, as well as global totals, from 1961 to 2008 (Global Footprint Network, 2011). The intent of the NFA is to provide scientifically robust and transparent calculations to highlight the relevance of biocapacity limits for decision-making. It also helps to underscore the importance of safeguarding the life-supporting ecosystem services enabling the biosphere to support humanity in the long term.

The calculations in the NFA are based primarily on data sets from UN agencies or affiliated organizations such as the Food and Agriculture Organization of the United Nations (FAOSTAT, 2011), the UN Statistics Division (UN Commodity Trade Statistics Database – UN Comtrade 2011), and the International Energy Agency (IEA 2011). Other data sources include studies in peer-reviewed journals and thematic collections - a complete list of source data sets is reported in Table 1.

[Table 1]

Most raw data is obtained in CSV (comma separated value) or similar flat text file format. Some data arrangement and supporting calculations are performed using Microsoft Excel, after which raw data and intermediate results are stored in a MySQL database. Further data pre-processing is then performed by excecuting scripts within the database environment. The NFA calculations themselves are executed in an Excel workbook. A custom built software application manages the importation of data from the database into the NFA workbook, and writes NFA results back to a table in the database.

Results can be reported at the level of each individual product, land type, or aggregated into a single number (see Figure 1) - the latter being the most commonly used reporting format. Normalizing factors, referred as the yield factor and equivalence factor, are used to scale the contribution of each single land type so that values can be added up into an aggregate number (see sections 4.2 and 4.3). Aggregating results into a single value has the advantage of monitoring the combined demand of anthropogenic activities against nature’s overall regenerative capacity. It also helps to understand the complex relationships between the many environmental problems exposing humanity to a "peak-everything" situation. This is a unique feature since pressures are more typically evaluated independently (climate change, fisheries collapse, land degradation, land use change, food consumption, etc.).

[Figure 1]

National Footprint Accounts are maintained and updated annually by Global Footprint Network. Each time methodological improvements are implemented and a new NFA Edition is released, Ecological Footprint and biocapacity values are back calculated from the most recent year in order to ensure consistency across the historical time trends.

4. Calculation methodology

4.1 Ecological Footprint and biocapacity: basic equations

The Ecological Footprint measures appropriated biocapacity across five distinct land use types. This is contrasted with six demand categories. The reason is that two demand categories, forest products and carbon sequestration, compete both for the same biocapacity category: forest land.
Average bioproductivity differs between various land use types, as well as between countries for any given land use type. For comparability across land use types and countries, Ecological Footprint and biocapacity are usually expressed in units of world-average bioproductive area, referred to as global hectares (gha).
Global hectares provide more information than simply weight - which does not capture the extent of land and sea area used - or physical area - which does not capture how much ecological production is associated with that land. Two important type of coefficients, the yield factors (YF) and the equivalence factors (EQF), allow results to be expressed in terms of global hectares (Monfreda et al., 2004; Galli et al., 2007), providing comparability between various countries’ Ecological Footprints as well as biocapacity values.

For a given nation, the Ecological Footprint of production, EF_P, represents primary demand for biocapacity and is calculated as

$$\mathrm{EF}_{\mathrm{P}} = \sum_i \frac{P_i}{Y_{N,i}} \cdot YF_{N,i} \cdot EQF_i = \sum_i \frac{P_i}{Y_{W,i}} \cdot EQF_i \qquad \text{(Equation 1)}$$

where P is the amount of each primary product i that is harvested (or carbon dioxide emitted) in the nation; $Y_{N,i}$ is the annual national average yield for the production of commodity i (or its carbon uptake capacity in cases where P is CO_2); $YF_{N,i}$ is the country-specific yield factor for the production of each product i; $Y_{W,i}$ is the average world yield for commodity i; and EQF_i is the equivalence factor for the land use type producing products i.

The equivalence of the second and third terms in Equation 1 arises from the definition of $YF_{N,i}$ as the ratio between $Y_{N,i}$ and $Y_{W,i}$ (see section 4.2). It is this last manifestation that is used in the NFA calculations.

A variety of derived products is also tracked in the NFA (see Table 1), for which production yields (Y_W) have to be calculated before implementation of Equation 1. Primary and derived goods are related by product specific extraction rates. The extraction rate for a derived product, $EXTR_D$, is used to calculate its effective yield as follows:

$$Y_{W,D} = Y_{W,P} \cdot EXTR_D \qquad \text{(Equation 2)}$$

where $Y_{W,D}$ and $Y_{W,P}$ are the world-average yield for the derived and the primary product, respectively.

Often $EXTR_D$ is simply the mass ratio of derived product to primary input required. This ratio is known as the technical conversion factor (FAO, 2000) for the derived product, denoted as TCF_D below. There are a few cases where multiple derived products are created simultaneously from the same primary product. For example, soybean oil and soybean cake are both extracted simultaneously from the same primary product, in this case soybean. In this situation, summing the primary product equivalents of the derived products would lead to double counting. To resolve this problem, the Ecological Footprint of the primary product must be shared between the simultaneously derived goods. The generalized formula for the extraction rate for a derived good D is

$$EXTR_D = \frac{TCF_D}{FAF_D} \qquad \text{(Equation 3)}$$

where FAF_D is the Footprint allocation factor. This allocates the Footprint of a primary product between simultaneously derived goods according to the TCF-weighted prices. The prices of derived goods represent their relative contributions to the incentive for the harvest of the primary product. The equation for the Footprint allocation factor of a derived product is

$$FAF_D = \frac{TCF_D \cdot V_D}{\sum TCF_i \cdot V_i} \qquad \text{(Equation 4)}$$

where V_i is the market price of each simultaneous derived product. For a production chain with only one derived product, then, FAF_D is 1 and the extraction rate is equal to the technical conversion factor.

For a given country, the biocapacity BC is calculated as follows:

$$BC = \sum_i A_{N,i} \cdot YF_{N,i} \cdot EQF_i \qquad \text{(Equation 5)}$$

where $A_{N,i}$ is the bioproductive area that is available for the production of each product *i* at the country level, $YF_{N,i}$ is the country-specific yield factor for the land producing products *i*, and EQF_i is the equivalence factor for the land use type producing each product *i*.

4.2 Yield factors

Yield factors (YFs) account for countries' differing levels of productivity for particular land use types.[1] YFs are country-specific and vary by land use type and year. They may reflect natural factors such as differences in precipitation or soil quality, as well as anthropogenic differences such as management practices.

The YF is the ratio of national average to world average yields. It is calculated in terms of the annual availability of usable products. For any land use type *L*, a country's yield factor YF_L, is given by

$$YF_L = \frac{\sum_{i \in U} A_{W,i}}{\sum_{i \in U} A_{N,i}} \qquad \text{(Equation 6)}$$

where *U* is the set of all usable primary products that a given land use type yields, and $A_{W,i}$ and $A_{N,i}$ are the areas necessary to furnish that country's annually available amount of product *i* at world and national yields, respectively. These areas are calculated as

$$A_{N,i} = \frac{P_i}{Y_{N,i}} \text{ and } A_{W,i} = \frac{P_i}{Y_{W,i}} \qquad \text{(Equation 7)}$$

where P_i is the total national annual growth of product *i*, and $Y_{N,i}$ and $Y_{W,i}$ are national and world yields for the same product, respectively. Thus $A_{N,i}$ is always the area that produces a given product *i* within a given country, while $A_{W,i}$ gives the equivalent area of world-average land yielding the same product *i*.

With the exception of cropland, all land use types included in the National Footprint Accounts provide only a single primary product *i*, such as wood from forest land or grass from grazing land. For these land use types, the equation for the YF simplifies to

$$YF_L = \frac{Y_{N,i}}{Y_{W,i}} \qquad \text{(Equation 8)}$$

Due to the difficulty of assigning a yield to built-up land, the YF for this land use type is assumed to be the same as that for cropland (in other words urban areas are assumed to be built on or near productive agricultural lands). For lack of detailed global datasets, areas inundated by hydroelectric reservoirs are presumed to have previously had world average productivity. The YF for the carbon Footprint is assumed to be the same as that for forest

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[1] For example, the average hectare of pasture in New Zealand produces more grass than a world average hectare of pasture land. Thus, in terms of productivity, one hectare of grassland in New Zealand is equivalent to more than one world average grazing land hectare; it is potentially capable of supporting more meat production. Table 1 shows the yield factors calculated for several countries in the 2011 Edition of Global Footprint Network's National Footprint Accounts.

land, due to limited data availability regarding the carbon uptake of other land use types. All inland waters are assigned a YF of one, due to the lack of a comprehensive global dataset on freshwater ecosystem productivities (see Table 2).

[Table 2]

4.3 Equivalence factors

In order to combine the Ecological Footprint or biocapacity of different land-use types, a second coefficient is necessary (Galli et al., 2007). Equivalence factors (EQFs) convert the areas of different land use types, at their respective world average productivities, into their equivalent areas at global average bioproductivity across all land use types. EQFs vary by land use type as well as by year.

The rationale behind EQF calculation is to weight different land areas in terms of their inherent capacity to produce human-useful biological resources. The weighting criterion is not the actual quantity of biomass produced, but what each hectare would be able to inherently deliver.

As an approximation of inherent capacity, EQFs are currently calculated[2] using suitability indexes from the Global Agro-Ecological Zones model combined with data on the actual areas of cropland, forest land, and grazing land area from FAOSTAT (FAO and IIASA, 2000; FAO ResourceSTAT Statistical Database 2008). The GAEZ model divides all land globally into five categories, based on calculated potential crop productivity under assumption of agricultural input. All land is assigned a quantitative suitability index from among the following:

- Very Suitable (VS) – 0.9
- Suitable (S) – 0.7
- Moderately Suitable (MS) – 0.5
- Marginally Suitable (mS) – 0.3
- Not Suitable (NS) – 0.1

The calculation of the EQFs assumes that within each country the most suitable land available will be planted to cropland, after which the most suitable remaining land will be under forest land, and the least suitable land will be devoted to grazing land. The EQFs are calculated as the ratio of the world average suitability index for a given land use type to the average suitability index for all land use types. Figure 2 shows a schematic of this calculation.

[Figure 2]

The total number of bioproductive land hectares is shown by the length of the horizontal axis. Vertical dashed lines divide this total land area into the three terrestrial land use types for which equivalence factors are calculated (cropland, forest, and grazing land). The length of

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[2] Actual Net Primary Production (NPP) values have been suggested for use in scaling land type productivity (Venetoulis and Talberth, 2008) and were also used in the earliest Footprint accounts; however, this would not allow incorporating the inherent productivity as, for instance, crop land is managed for maximum crop, not for maximum biomass production.

Potential NPP data - the NPP of useable biological materials that could be potentially available in the absence of human management - could theoretically be used as weighting factors (see Kitzes et al., 2009). A global data set exists (FAO, 2006) and research is under way at Global Footprint Network to assess the possibility of using potential NPP data in calculating EQFs.

each horizontal bar in the graph shows the total amount of land available with each suitability index. The vertical location of each bar reflects the suitability score for that suitability index, between 10 and 90.

For the reasons detailed above, the EQF for built-up land is set equal to that for cropland, except there is clear evidence that built-up land does not sit on cropland. EQF of carbon uptake land is set equal to that of forest land since the carbon Footprint is assumed to draw on forest area. The EQF for hydroelectric reservoir area is set equal to one, reflecting the assumption that hydroelectric reservoirs flood world average land. The EQF for marine area is calculated such that the amount of calories of salmon that can be produced by a single global hectare of marine area will be equal to the amount of calories of beef produced by a single global hectare of pasture. This is based on the assumption that a calorie from animal protein from land and from sea would be considered to be of equivalent resource value to people. The EQF for inland water is set equal to that of marine area.

Table 3 shows the EQFs for the land use types in the 2011 National Footprint Accounts, data year 2008.

[Table 3]

Cropland’s EQF of 2.51 indicates that world-average cropland productivity was more than double the average productivity for all land combined. This same year, grazing land had an EQF of 0.46, showing that grazing land was, on average, 46 per cent as productive as the world-average bioproductive hectare.

4.4 A Consumer approach for the National Footprint Accounts

All manufacturing processes rely to some degree on the use of biocapacity to provide material inputs and remove wastes at various points in the production chain. Thus all products carry with them an embodied Footprint, and international trade flows can be seen as flows of embodied demand for biocapacity.

In order to keep track of both the direct and indirect biocapacity needed to support people’s consumption patterns, the National Footprint Accounts use a consumer-based approach; for each land use type, the Ecological Footprint of consumption (EF_C) is thus calculated as

$$EF_C = EF_P + EF_I - EF_E \qquad \text{(Equation 9)}$$

where EF_P is the Ecological Footprint of production and EF_I and EF_E are the Footprints embodied in imported and exported commodity flows, respectively. For each traded product, EF_I and EF_E are calculated as in equation 1, with Production P being the amount of product imported or exported, respectively.

The National Footprint Accounts calculate the Footprint of apparent consumption, as data on stock changes for various commodities are generally not available. One of the advantages of calculating Ecological Footprints at the national level is that this is the level of aggregation at which detailed and consistent production and trade data are most readily available. Such information is essential in properly allocating the Footprints of traded goods to their final consumers (see Figure 3).

[Figure 3]

5. Land use types in the National Footprint Accounts

The Ecological Footprint represents demand for ecosystem products and services in terms of appropriation of various land use types (see Section 1), while biocapacity represents the productivity available to serve each use. In 2008, the area of biologically productive land and water on Earth was approximately 12 billion hectares. After multiplying by the EQFs, the relative area of each land use type expressed in global hectares differs from the distribution in actual hectares as shown in Figure 4.

[Figure 4]

National Footprint Accounts are specifically designed to yield conservative estimates of global overshoot as Ecological Footprint values are consistently underestimated while actual rather than sustainable biocapacity values are used. For instance, human demand, as reported by the Ecological Footprint, is underestimated because of the exclusion of freshwater consumption, soil erosion, GHGs emissions other than CO_2 as well as impacts for which no regenerative capacity exists (e.g. pollution in terms of waste generation, toxicity, eutrophication, etc.). In turn, the biosphere's supply is overestimated as both the land degradation and the long-term sustainability of resource extraction is not taken into account.

5.1 Cropland

Cropland consists of the area required to grow all crop products, including livestock feeds, fish meals, oil crops and rubber. It is the most bioproductive of the land use types included in the National Footprint Accounts. In other words, the number of global hectares of cropland is large compared to the number of physical hectares of cropland in the world, as shown in Figure 4.

Worldwide in 2008 there were 1.53 billion hectares designated as cropland[3] (FAO ResourceSTAT Statistical Database 2011). The National Footprint Accounts calculate the Footprint of cropland using data on production, import and export of primary and derived agricultural products. The Footprint of each crop type is calculated as the area of cropland that would be required to produce the harvested quantity at world-average yields.

Cropland biocapacity represents the combined productivity of all land devoted to growing crops, which the cropland Footprint cannot exceed. As an actively managed land use type, cropland has yields of harvest equal to yields of growth by definition and thus it is not possible for the Footprint of production of this land use type to exceed biocapacity within any given area (Kitzes et al., 2009). The eventual availability of data on present and historical sustainable crop yields would allow improving the cropland footprint calculation and tracking crop overexploitation (Bastianoni et al., 2012).

5.2 Grazing Land

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[3] In the National Footprint Accounts, "cropland" is defined to match the FAO land use category 'Arable land and Permanent crops' – FAO code 6620.

The grazing land Footprint measures the area of grassland used in addition to crop feeds to support livestock. Grazing land comprises all grasslands used to provide feed for animals, including cultivated pastures as well as wild grasslands and prairies. In 2008, there were 3.37 billion hectares of land worldwide classified as grazing land[4] (FAO ResourceSTAT Statistical Database 2011). The grazing land Footprint is calculated following Equation 1, where yield represents average above-ground NPP for grassland. The total demand for pasture grass, P_{GR}, is the amount of biomass required by livestock after cropped feeds are accounted for, following the formula

$$P_{GR} = TFR - F_{Mkt} - F_{Crop} - F_{Res} \qquad \text{(Equation 10)}$$

where TFR is the calculated total feed requirement, and F_{Mkt}, F_{Crop} and F_{Res} are the amounts of feed available from general marketed crops, crops grown specifically for fodder, and crop residues, respectively.

Since the yield of grazing land represents the amount of above-ground primary production available in a year, and there are no significant prior stocks to draw down, overshoot is not physically possible over extended periods of time for this land use type. For this reason, a country's grazing land Footprint of production is prevented from exceeding local grazing land biocapacity in the National Footprint Accounts.

The grazing land calculation is the most complex in the National Footprint Accounts and significant improvements have taken place over the past seven years; including improvements to the total feed requirement, inclusion of fish and animal products used as livestock feed, and inclusion of livestock food aid (see Ewing et al., 2010a for further details).

5.3 Fishing Grounds

The fishing grounds Footprint is calculated based on the annual primary production required to sustain a harvested aquatic species. This primary production requirement, denoted *PPR*, is the mass ratio of harvested fish to annual primary production needed to sustain that species, based on its average trophic level. Equation 11 provides the formula used to calculate *PPR*. It is based on the work of Pauly and Christensen (1995).

$$PPR = CC \cdot DR \cdot \left(\frac{1}{TE}\right)^{(TL-1)} \qquad \text{(Equation 11)}$$

where CC is the carbon content of wet-weight fish biomass, DR is the discard rate for bycatch, TE is the transfer efficiency of biomass between trophic levels, and TL is the trophic level of the fish species in question.

In the National Footprint Accounts, DR is assigned the global average value of 1.27 for all fish species, meaning that for every ton of fish harvested, 0.27 tonnes of bycatch are also harvested (Pauly and Christensen 1995). This bycatch rate is applied as a constant coefficient in the PPR equation, reflecting the assumption that the trophic level of the bycatch is the same as that of the primary catch species. These approximations are employed for lack of

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[4] In the National Footprint Accounts, "grazing land" is defined to match the FAO land use category 'Permanent meadows and pastures' – FAO code 6655.

higher resolution data on bycatch. *TE* is assumed to be 0.1 for all fish, meaning that 10% of biomass is transferred between successive trophic levels (Pauly and Christensen, 1995).

The estimate of annually available primary production used to calculate marine yields is based on estimates of the sustainable annual harvests of 19 different aquatic species groups (Gulland, 1971). These quantities are converted to primary production equivalents using Equation 11, and the sum of these is taken to be the total primary production requirement that global fisheries may sustainably harvest. Thus the total sustainably harvestable primary production requirement, PP_S, is calculated as

$$PP_S = \sum \left(Q_{S,i} \cdot PPR_i \right) \qquad \text{(Equation 12)}$$

where $Q_{S,i}$ is the estimated sustainable catch for species group i, and PPR_i is the primary production requirement corresponding to the average trophic level of species group i. This total harvestable primary production requirement is allocated across the continental shelf areas of the world to produce biocapacity estimates. Thus the world-average marine yield Y_M, in terms of PPR, is given by

$$Y_M = \frac{PP_S}{A_{CS}} \qquad \text{(Equation 13)}$$

where PP_S is the global sustainable harvest from Equation 12, and A_{CS} is the global total continental shelf area.

Significant improvements have taken place over the past seven years in the calculation of the fishing grounds section of the National Footprint Accounts; including revision of many fish extraction rates, inclusion of aquaculture production, and inclusion of crops used in aquafeeds (see Ewing et al., 2010a for further details on such improvements).

5.4 Forest Land

The forest land Footprint measures the annual harvest of fuel wood and timber to supply forest products. Worldwide in 2008 there were 4.04 billion hectares of forest land area in the world (FAO ResourceSTAT Statistical Database 2011).[5]

The yield used in the forest land Footprint is the net annual increment (NAI) of merchantable timber per hectare. Timber productivity data from the UNEC and FAO Forest Resource Assessment and the FAO Global Fiber Supply are utilized to calculate the world average yield of 1.81 m^3 of harvestable wood per hectare per year (UNECE and FAO 2000; FAO 1998).

The National Footprint Accounts calculate the Footprint of forest land according to the production quantities of 13 primary timber products and three wood fuel products. Trade flows include 30 timber products and 3 wood fuel products.

5.5 Carbon Footprint

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[5] In the National Footprint Accounts, "forest" is defined to match the FAO land use category 'Forest Area' – FAO code 6661. Due to data limitation, current accounts do not distinguish between forests for forest products, for long-term carbon uptake, or for biodiversity reserves.

The uptake land to accommodate the carbon Footprint is the only land use type included in the Ecological Footprint that is exclusively dedicated to tracking a waste product: carbon dioxide.[6] In addition, it is the only land use type for which biocapacity is not explicitly defined.

CO_2 is released into the atmosphere from a variety of sources, including human activities such as burning fossil fuels and certain land use practices; as well as natural events such as forest fires, volcanoes, and respiration by animals and microbes.

Many different ecosystem types have the capacity for long-term storage of CO_2, including the land use types considered in the National Footprint Accounts such as cropland or grassland. However, since most terrestrial carbon uptake in the biosphere occurs in forests, and to avoid overestimations, carbon uptake land is assumed to be forest land by the Ecological Footprint methodology. For this reason, it is considered to be a subcategory of forest land. Therefore, in the 2011 Edition, forest for timber and fuelwood is not separated from forest for carbon uptake.[7]

The demand on carbon uptake land is the largest contributor to humanity's current total Ecological Footprint and increased more than tenfold from 1961 to 2008. However, in lower income countries the carbon Footprint is often not the dominant contributor to the overall Ecological Footprint.

Analogous to Equation 1, the formula for the carbon Ecological Footprint (EF_c) is

$$\mathrm{EF_C} = \frac{\mathrm{P_C} \cdot \left(1 - \mathrm{S_{Ocean}}\right)}{\mathrm{Y_C}} * \mathrm{EQF} \qquad \text{(Equation 14)}$$

where P_C is the annual anthropogenic emissions (production) of carbon dioxide, S_{Ocean} is the fraction of anthropogenic emissions sequestered by oceans in a given year (see section 6.3 for further details) and Y_C is the annual rate of carbon uptake per hectare of world average forest land.

5.6 Built-Up Land

The built-up land Footprint is calculated based on the area of land covered by human infrastructure: transportation, housing, industrial structures and reservoirs for hydroelectric power generation. In 2008, the built-up land area of the world was approximately 170 million hectares. The 2011 Edition of the National Footprint Accounts assumes that built-up land occupies what would previously have been cropland. This assumption is based on the observation that human settlements are generally situated in fertile areas with the potential for supporting high yielding cropland (Imhoff et al., 1997; Wackernagel et al., 2002).

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[6] Today, the term "carbon footprint" is widely used as shorthand for the amount of anthropogenic greenhouse gas emissions; in the Ecological Footprint methodology however, it translates the amount of anthropogenic carbon dioxide into the amount of productive land and sea area required to sequester carbon dioxide emissions. (See Galli et al. (2012) for additional information.)

[7] Global Footprint Network has not yet identified reliable global data sets on how much of the forest areas are dedicated to long-term carbon uptake. Hence, the National Footprint Accounts do not distinguish which portion of forest land is dedicated to forest products and how much is permanently set aside to provide carbon uptake services. Also note that other kind of areas might be able to provide carbon uptake services.

For lack of a comprehensive global dataset on hydroelectric reservoirs, the National Footprint Accounts assume these to cover areas in proportion to their rated generating capacity. Built-up land always has a biocapacity equal to its Footprint since both quantities capture the amount of bioproductivity lost to encroachment by physical infrastructure. In addition, the Footprint of production and the Footprint of consumption of built-up land are always equal in the National Footprint Accounts as built-up land embodied in traded goods is not currently included in the calculation due to lack of data. This omission is likely to cause overestimates of the built-up Footprint of exporting countries and underestimates of the built-up Footprint of importing countries.

6. Methodological changes between the 2010 and 2011 edition of the National Footprint Accounts

A formal process is in place to assure continuous improvement of the National Footprint Accounts (NFA) methodology. Coordinated by Global Footprint Network, this process is supported by its partners and by the National Footprint Accounts Review Committee, as well as other stakeholders.

There have been three primary motivations for revisions to the calculation method of the National Footprint Accounts:

- to adapt to changes in the organization of the source data;
- to respond to issues raised in outside reviews; and
- to increase the detail and accuracy of the NFA calculations.

This section describes each of the calculation method changes implemented since the 2010 Edition of the National Footprint Accounts.

6.1 Data Cleaning

In the NFA 2011, a source data cleaning algorithm was implemented different to the algorithm used in NFA 2010. The new algorithm is used to reduce (1) spikes and troughs and (2) inconsistent reporting in the time series of source data sets. The new algorithm excludes data points that are a fixed distance from the median value of the reference time series data. The algorithm also involves interpolation to fill in data gaps based on the Akaike Information Criterion (Akaike, 1978). Further details on the data cleaning algorithm used in the NFA 2011 Edition are available upon request from Global Footprint Network.

6.2 Constant global hectares: a revised method to calculate Ecological Footprint and biocapacity time series

Ecological Footprint and biocapacity calculations are usually presented in units of global hectares (see section 4). Historically, Ecological Footprint analyses have utilized a Yield Factor (YF) for each land use type to capture the difference between local and global productivity. The various land use types are then converted into global hectares using equivalence factors (EQFs) for each land use type. In every year, the total biocapacity of the planet, expressed in global hectares, equals the total number of biologically productive physical hectares on Earth (Kitzes et al., 2007b). Therefore, the number of global hectares of biocapacity available on the planet in any given year only reflects the total physical bioproductive area of the planet and is entirely insensitive to changes in yields (Wackernagel et al., 2004). This can cause difficulties of interpretation when comparing changes in biocapacity and Ecological Footprint over time as it is hard to represent actual variations in demand and supply of regenerative capacity (Haberl et al., 2001).

In the 2011 Edition of the National Footprint Accounts, we have implemented a method for reporting Ecological Footprint and biocapacity time trends in 'constant global hectares' (hectares normalized to have world-average bioproductivity in a single reference year). This is realized via the introduction of a set of world-average Intertemporal Yield Factors (IYFs). A constant global hectare concept allows trends in both total bioproductive area and trends in yield and productivity to be shown explicitly. IYFs are calculated for each year and land use type in order to track changes in the world-average bioproductivity over time of each land type.

For any given land type producing products *i*, in a given year *j*, with a selected base year *b*, a world average Intertemporal Yield Factor (IYF_W) is thus calculated as:

$$IYF_{W,j} = \frac{\sum_i \frac{P_{W,i,j}}{Y_{W,i,b}}}{\sum_i \frac{P_{W,i,j}}{Y_{W,i,j}}} \qquad \text{(Equation 15)}$$

where P is the amount of a product harvested (or CO_2 emitted) and Y_W is the world-average product-specific yield. For the 2011 Edition of the NFAs, the selected base year is 2008 (the most recent year over the analyzed period).

IYFs complement the function of the Yield Factors (YF) currently employed in the National Footprint Accounts. While YFs compare the yield of a given land use type in a given nation with the world-average yield for that same land use type, IYFs account for changes in the world-average yield of that same land use type over time.

Ecological Footprint time series are therefore calculated as follows:

$$EF = \sum_i \frac{P_{N,i,j}}{Y_{N,i,j}} \cdot YF_{N,i,j} \cdot IYF_{W,i,j} \cdot EQF_{i,j} = \sum_i \frac{P_{N,i,j}}{Y_{W,i,j}} \cdot IYF_{W,i,j} \cdot EQF_{i,j} \qquad \text{(Equation 16)}$$

Similarly, biocapacity time series are calculated in terms of constant gha as follows:

$$\mathrm{BC} = \sum_i A_{N,i,j} \cdot YF_{N,i,j} \cdot IYF_{W,i,j} \cdot EQF_{i,j} \qquad \text{(Equation 17)}$$

Where, for any product *i*, in a given year *j*, A_N represents the bioproductive area available at the country level, and YF_N, IYF_W and EQF, are the country-specific yield factor, the world average Intertemporal Yield Factor, and the equivalence factor for the land use type producing that product, respectively.

Calculating IYFs for each land use type requires production quantity and yield data over time. While production quantity data is available for all products tracked by the NFAs over the period 1961-2008, time series yield data are available for crop-based products only. This renders the calculation of IYFs currently possible for the 'cropland' land use type only; in the absence of available data, IYF time series values for all other land types have been set equal to 1.

6.3 Ocean Uptake Changes

A fraction of human-induced carbon emissions is annually taken up by the oceans from the atmosphere. To track this fraction, National Footprint Accounts have historically used an averaged ocean uptake value of 1.8 Pg C yr^{-1} based on two data points drawn from the third IPCC assessment report (IPCC, 2001). This quantity has been held constant over time leading to the estimation of an 82% emissions uptake from the ocean back in the year 1961, which is likely to be unrealistic. This caused an underestimation of the carbon Footprint component in the early decades tracked by the NFAs.

To create an appropriate time series for the percent uptake of anthropogenic carbon emissions into the ocean, in the 2011 Edition of the National Footprint Accounts we have used ocean uptake data (in Pg C yr^{-1}) from Khatiwala et al (2009) and divided this data by the corresponding (total anthropogenic) carbon emissions data (in Pg C yr^{-1}) from the Carbon Dioxide Information Analysis Center (Marland et al., 2007). The outcome of the revised calculation shows a relatively constant percentage uptake for oceans, varying between 28% and 35% over the period 1961-2008.

Implementing this change has caused a major shift in the total humanity's Footprint value from 1961 to the late 1990s; this has significantly contributed to a shift in the global overshoot state - the first occurrence of overshoot is calculated as occurring in the early 1970s (in the NFA 2011 Edition), changed from the mid 1970s (in the NFA 2010 Edition).

7. National Footprint Accounts' limitations

The National Footprint Accounts only aim at measuring whether or not humans are able to live within the Biosphere's ecological budget. To answer this research question, a systemic approach is used to assess, in a combined way, the impact of pressures that are usually evaluated independently. Therefore, NFAs have been developed as a resource accounting framework, where the various pressures are first analyzed independently and results are then aggregated into a single number (see section 3 and Figure 1). Aggregation, however, has the drawback of implying a greater degree of additivity and substitutability between the included land use types than is probably realistic (DG Environment, 2008; Giljum et al., 2009; Kitzes et al., 2009; Wiedmann and Barrett, 2010).

The quality, reliability and validity of the National Footprint Accounts are dependent upon the level of accuracy and availability of a wide range of datasets, many of which have incomplete coverage, and most of which do not specify confidence limits. Considerable care is taken to minimize any data inaccuracies or calculation errors that might distort the National Footprint Accounts, including inviting national governments to collaboratively review the assessment of their country for accuracy (e.g., Abdullatif and Alam, 2011; Hild et al., 2010; von Stokar et al., 2006). In addition, the Ecological Footprint methodology is continually being refined and efforts are made to improve the transparency of the National Footprint Accounts and the related written documentation (Gracey et al., 2012; Kitzes et al., 2009), allowing for more effective internal and external review.

Overall, the National Footprint Accounts are constructed to err on the side of over-reporting biocapacity and under-reporting Ecological Footprints, making it less likely that any errors will significantly overstate the scale of human demand for regenerative capacity. Moreover, every new edition of the National Footprint Accounts can rely on the use of more comprehensive data sets and independent data sources, more consistent and reliable data, and a more robust calculation process, leading to more reliable Ecological Footprint and biocapacity values for nations and the world.

A detailed list of strengths and weaknesses of the Ecological Footprint methodology and limitations of the National Footprint Accounts, can be found in Galli et al (2011) and Ewing et al (2010b), respectively.

Conclusions

In an increasingly resource constrained world, accurate and effective resource accounting systems are needed if nations, cities and companies want to stay competitive. National Footprint Accounts is one such accounting system, designed to track human demand on the regenerative and absorptive capacity of the biosphere.

In 1961, the first year for which the National Footprint Accounts are available, humanity's Ecological Footprint was approximately half of what the biosphere could supply annually—humanity was living off the planet's annual ecological interest, not drawing down its principal (Figure 5). According to the 2011 Edition of the National Footprint Accounts, human demand first exceeded the planet's biocapacity in the early 1970s. Since 1961, humanity's overall Footprint has more than doubled, and overshoot has continued to increase, reaching 52% in 2008.

The various land use types are stacked to show the total Ecological Footprint. Humanity's Ecological Footprint in 2008 consisted of 22% cropland, 8% grazing land, 10% forest land, 4% fishing ground, 54% carbon uptake land, and 2% built-up land. As these annual deficits accrue into an ever larger ecological debt, ecological reserves are depleting, and wastes such as CO_2 are accumulating in the biosphere and atmosphere.

[Figure 5]

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TABLE 1: Input data to the Ecological Footprint and biocapacity calculation. Approximately 61 million data points are used in the National Footprint Accounts 2011 Edition (6,000 data points per country and year).

DATASET	SOURCE	DESCRIPTION
Production of primary agricultural products	FAO ProdSTAT	Data on physical quantities (tonnes) of primary products produced in each of the considered countries
Production of crop-based feeds used to feed animals	Feed from general marketed crops data is directly drawn from the SUA/FBS from FAOSTAT Data on crops grown specifically for fodder is drawn directly from the FAO ProdSTAT	Data on physical quantities (tonnes) of feeds, by type of crops, available to feed livestock
Production of seeds	Data on crops used as seeds is calculated by Global Footprint Network based on data from the FAO ProdSTAT	Data on physical quantities (tonnes) of seed
Import and Export of primary and derived agricultural and livestock products	FAO TradeSTAT	Data on physical quantities (tonnes) of products imported and exported by each of the considered countries
Import and Export of non-agricultural commodities	COMTRADE	Data on physical quantities (kg) of products imported and exported by each of the considered countries
Livestock crop consumption	Calculated by Global Footprint Network based upon the following datasets: • FAO Production for primary Livestock • Haberl et al., 2007.	Data on crop-based feed for livestock (tonnes of dry matter per year), split into different crop categories
Production of primary forestry products as well as	FAO ForeSTAT	Data on physical quantities (tonnes and m^3) of products

import and export of primary and derived forestry products		(timber and wood fuel) produced, imported and exported by each country
Production of primary fishery products as well as import and export of primary and derived fishery products	FAO FishSTAT	Data on physical quantities (tonnes) of marine and inland fish species landed as well as import and export of fish commodities
Carbon dioxide emissions by sector	International Energy Agency (IEA)	Data on total amounts of CO_2 emitted by each sector of a country's economy
Built-up/infrastructure areas	A combination of data sources is used, in the following order of preference: 1. CORINE Land Cover 2. FAO ResourceSTAT 3. Global Agro-Ecological Zones (GAEZ) Model 4. Global Land Cover (GLC) 2000 5. Global Land Use Database from the Center for Sustainability and the Global Environment (SAGE) at University of Wisconsin	Built-up areas by infrastructure type and country. Except for data drawn from CORINE for European countries, all other data sources only provide total area values
Cropland yields	FAO ProdSTAT	World average yield for 164 primary crop products
National yield factors for cropland	Calculated by Global Footprint Network based on cropland yields and country specific unharvested percentages	Country specific yield factors for cropland
Grazing land yields	Chad Monfreda (personal communication), 2008. SAGE, University of Wisconsin, Madison	World average yield for grass production. It represents the average above-ground edible net primary production for grassland available for consumption by ruminants
Fish yields	Calculated by Global Footprint Network based on several data	World-average yields for fish species. They are based on the annual marine primary

	sources including: • Sustainable catch value (Gulland, 1971) • Trophic levels of fish species (Fishbase Database available at www.fishbase.org) • Data on discard factors, efficiency transfer, and carbon content of fish per tonne wet weight (Pauly and Christensen, 1995)	production equivalent
Forest yields	World average forest yield calculated by Global Footprint Network based on national Net Annual Increment (NAI) of biomass. NAI data is drawn from two sources: • Temperate and Boreal Forest Resource Assessment – TBFRA (UNECE and FAO 2000) • Global Fiber Supply Model – GFSM (FAO, 1998)	World average forest yield. It is based on the forests' Net Annual Increment of biomass. NAI is defined as the average annual volume over a given reference period of gross increment less that of neutral losses on all trees to a minimum diameter of 0 cm (d.b.h.)
Carbon Uptake land yield	Calculated by Global Footprint Network based on data on terrestrial carbon sequestration (IPCC 2006) and the ocean sequestration percentage (Khatiwala et al., 2009) Further details can be found in (Gracey et al., 2012)	World average carbon uptake capacity. Though different ecosystems have the capacity to sequester CO_2, carbon uptake land is currently assumed to be forest land only by the Ecological Footprint methodology
Equivalence Factors (EQF)	Calculated by Global Footprint Network based on data on land cover and agricultural suitability Data on agricultural suitability is obtained from the Global Agro-Ecological Zones (GAEZ) model (FAO and IIASA, 2000). Land cover data drawn from the FAO ResourceSTAT database	EQF for crop, grazing, forest and marine land. Based upon the suitability of land as measured by the Global Agro-Ecological Zones model

TABLE 2: Sample Yield Factors for Selected Countries, 2008.

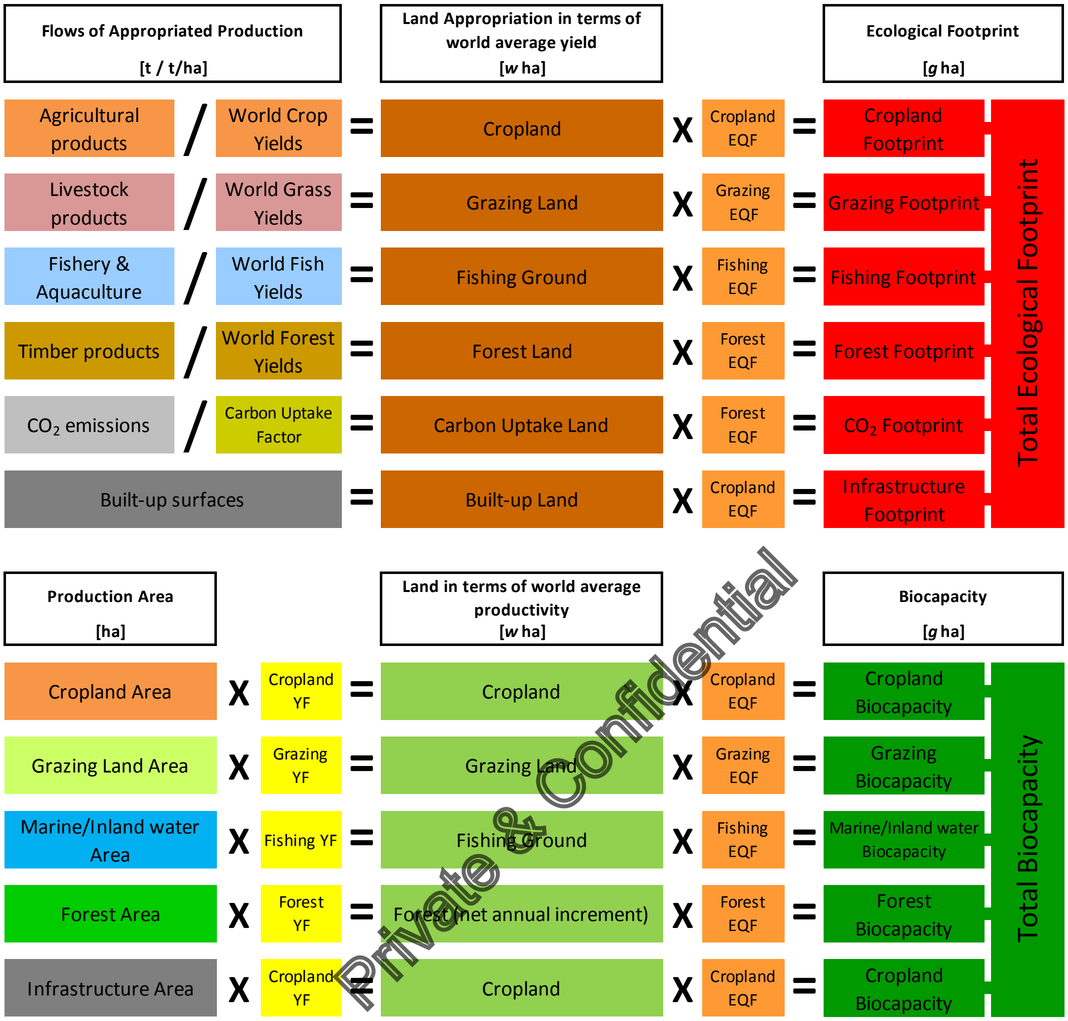
Countries	Cropland	Forest	Grazing Land	Fishing Grounds
World Average	1.0	1.0	1.0	1.0
Australia	0.4	0.3	0.8	1.0
Brazil	1.2	2.1	2.2	1.1
China	1.7	1.2	0.8	2.8
Congo	0.4	1.1	2.9	6.2
Czech Republic	1.5	3.9	2.2	0.0
Italy	1.6	1.7	1.9	0.8
Turkey	0.9	1.6	1.3	1.4
United Arab Emirates	0.7	1.5	0.1	2.1
United States of America	1.1	1.2	0.7	1.3

TABLE 3: Equivalence Factors, 2008.

Area Type	**Equivalence Factor** [global hectares per hectare]
Cropland	2.51
Forest	1.26
Grazing Land	0.46
Marine & Inland Water	0.37
Built-up Land	2.51

Figure(s)

FIGURE 1: National Footprint Accounts (NFA)’ accounting framework.



Flows of Appropriated Production [t / t/ha]

Land Appropriation in terms of world average yield [*w* ha]

Ecological Footprint [*g* ha]

Agricultural products / World Crop Yields = Cropland X Cropland EQF = Cropland Footprint

Livestock products / World Grass Yields = Grazing Land X Grazing EQF = Grazing Footprint

Fishery & Aquaculture / World Fish Yields = Fishing Ground X Fishing EQF = Fishing Footprint

Timber products / World Forest Yields = Forest Land X Forest EQF = Forest Footprint

CO_2 emissions / Carbon Uptake Factor = Carbon Uptake Land X Forest EQF = CO_2 Footprint

Built-up surfaces = Built-up Land X Cropland EQF = Infrastructure Footprint

Total Ecological Footprint

Production Area [ha]

Land in terms of world average productivity [*w* ha]

Biocapacity [*g* ha]

Cropland Area X Cropland YF = Cropland X Cropland EQF = Cropland Biocapacity

Grazing Land Area X Grazing YF = Grazing Land X Grazing EQF = Grazing Biocapacity

Marine/Inland water Area X Fishing YF = Fishing Ground X Fishing EQF = Marine/Inland water Biocapacity

Forest Area X Forest YF = Forest (net annual increment) X Forest EQF = Forest Biocapacity

Infrastructure Area X Cropland YF = Cropland X Cropland EQF = Cropland Biocapacity

Total Biocapacity

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FIGURE 2: Schematic Representation of equivalence factor calculations.

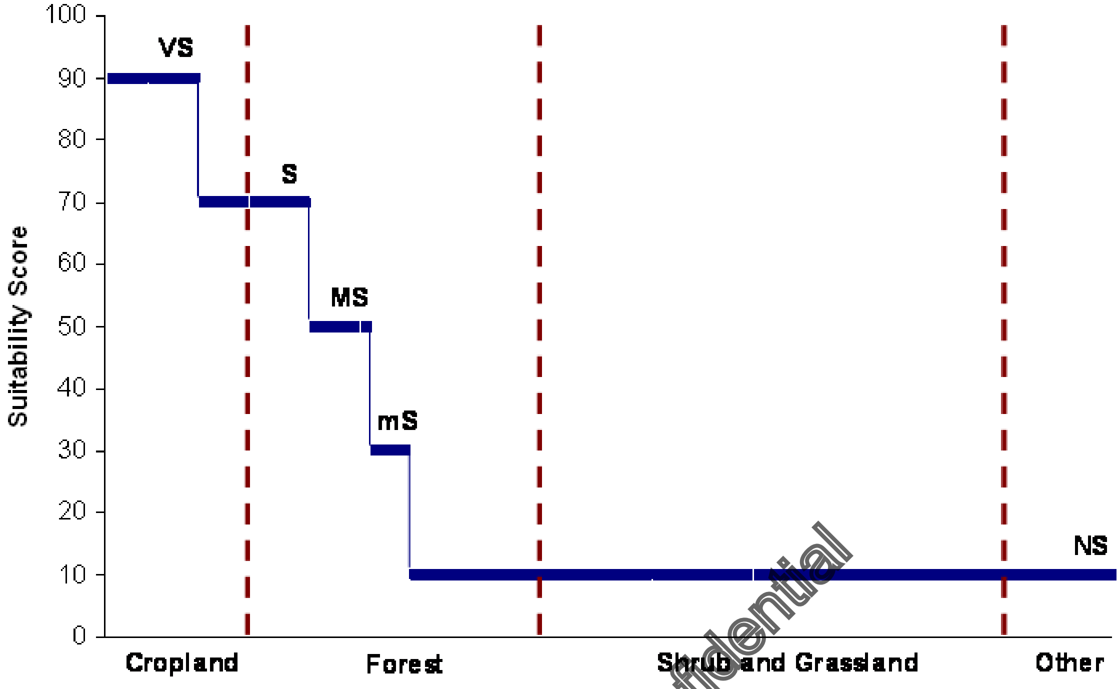

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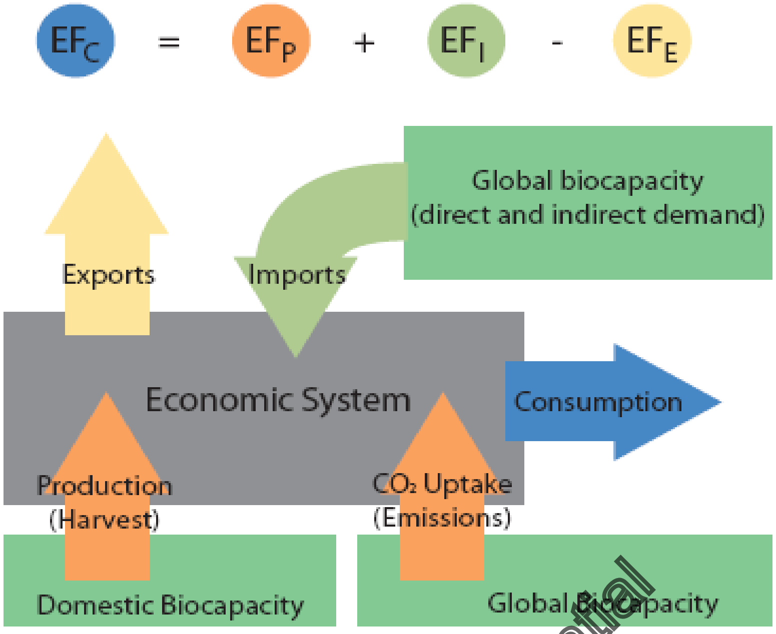
FIGURE 3: Schematic of direct and indirect demand for domestic and global biocapacity.



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Figure(s)

FIGURE 4: Relative area of land use types worldwide in hectares and global hectares, 2008.

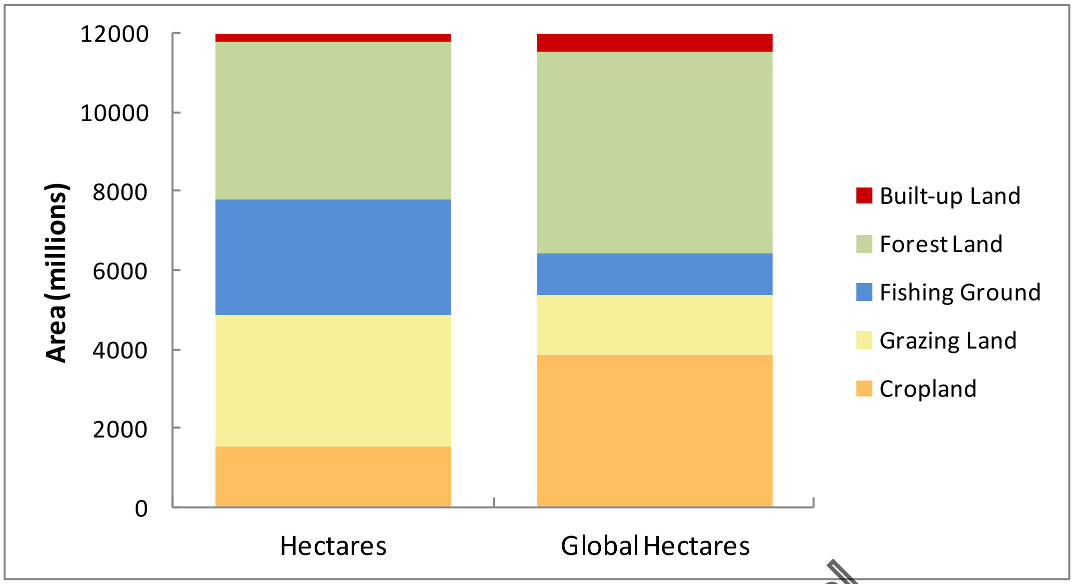

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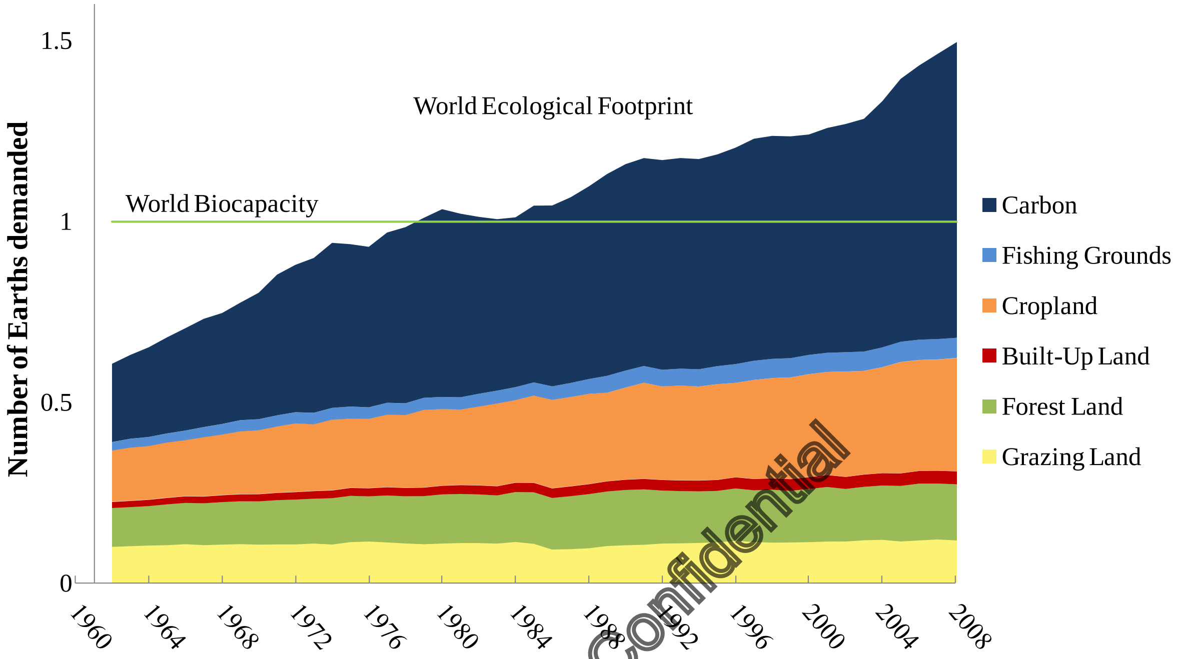
FIGURE 5: World overshoot according to the 2011 Edition of the National Footprint Accounts. Humanity's Ecological Footprint, expressed in number of planets demanded, has increased significantly over the past 47 years.



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