ENE425 Sustainable Energy and App Development

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Contents

2 Metrics: Ecological footprint and biocapacity **2**
2.1 Definition 2
2.1.1 Ecological footprint 3
2.1.2 Biocapacity 3
2.2 National footprint and biocapacity accounts 4
2.3 Methodology 4
2.3.1 Overview 4
2.3.2 Basic equations 4
2.3.3 The accounting principles are: 12
2.4 Analysis 13
2.5 Bibliography 14

Chapter 2

Metrics: Ecological footprint and biocapacity

In this chapter we study how to measure the ecological footprint per capita in every country. First, we define the concept. Second, we provide an overview of the concepts ecological footprint and biocapacity, Third, we present the methodology to work out the ecological footprint and the biocapacity. Finally, we present the historical trends of the ecological footprint and the biocapacity. The main text that we use in this chapter is Lin et al. (2019).

2.1 Definition

The Ecological Footprint is an account-based system of indicators whose underlying context is the recognition that Earth has a finite amount of biological production that supports all life on it. A widely recognized measure of sustainability, the Ecological Footprint provides an integrated, multiscale approach to tracking the use and overuse of natural resources, and the consequent impacts on ecosystems and biodiversity.

Ecological Footprint as an accounting system rather than a normative indicator.

How much of the biosphere's (or any region's) regenerative capacity does human activity ("activities" can refer to the entire consumption metabolism of humanity, the consumption of a given population (such as a city), a production process, or something as small and discreet as producing 1 kilogram of durum wheat spaghetti) demand? **How much of the planet's (or a region's) regenerative capacity does a defined activity require from nature?**

Footprint calculators:

There exist different online calculators to work out your personal footprint. To work out your footprint, and to know more about the methodology that they use to work out that footprint, you can visit:

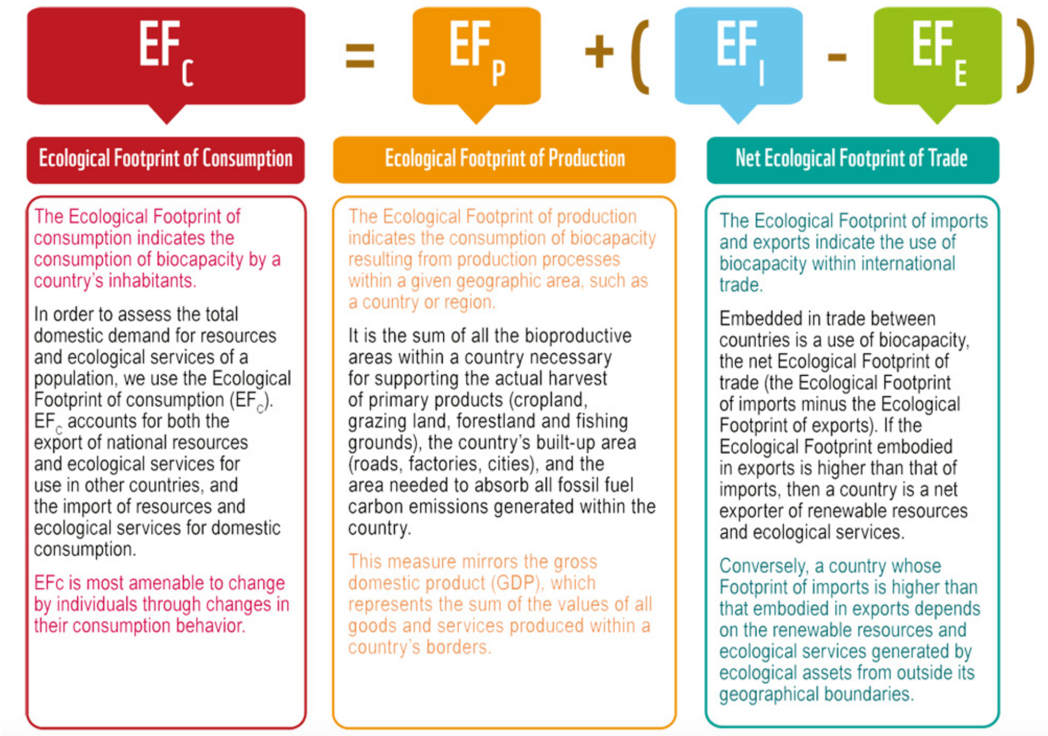
- Global Footprint Network calculator
- WWF calculator

Carbon calculators:

To work out your carbon emissions and to know more about projects to reduce carbon emissions visit: Carbon Footprint calculator.

To work out your **flight** carbon emissions visit: ICAO Carbon Emissions Calculator.

Figure 2.1: Footprint methodology



Source: footprintnetwork.org

2.1.1 Ecological footprint

The **Ecological Footprint** is derived by tracking how much biologically productive area it takes to provide for all the competing demands of people. These demands include space for food growing, fiber production, timber regeneration, absorption of carbon dioxide emissions from fossil fuel burning, and accommodating built infrastructure. A country's consumption is calculated by adding imports to and subtracting exports from its national production.

All commodities carry with them an embedded amount of bioproductive land and sea area necessary to produce them and sequester the associated waste. International trade flows can thus be seen as flows of embedded Ecological Footprint.

The Ecological Footprint uses yields of primary products (from cropland, forest, grazing land and fisheries) to calculate the area necessary to support a given activity.

2.1.2 Biocapacity

Biocapacity is measured by calculating the amount of biologically productive land and sea area available to provide the resources a population consumes and to absorb its wastes, given current technology and management practices. To make biocapacity comparable across space and time, **areas are adjusted proportionally to their biological productivity**. These adjusted areas are expressed in "global hectares". Countries differ in the productivity of their ecosystems, and this is reflected in the Accounts.

Results from this analysis shed light on a country's ecological impact. A country has an ecological reserve if its Footprint is smaller than its biocapacity; otherwise it is operating with an ecological deficit. The former are often referred to as ecological creditors, and the latter ecological debtors.

Today, most countries, and the world as a whole, are running ecological deficits. In fact, today over 85% of the world population lives in countries with an ecological deficit. The world's ecological deficit is referred to as global ecological overshoot.

Earth Overshoot Day.

Earth Overshoot Day marks the date when humanity has exhausted nature's budget for the year. For the rest of the year, we are maintaining our ecological deficit by drawing down local resource stocks and accumulating carbon dioxide in the atmosphere. We are operating in overshoot.

For more information about the Earth Overshoot Day visit: Earth Overshoot Day (Global Footprint Network link).

2.2 National footprint and biocapacity accounts

National Footprint and Biocapacity Accounts (NFAs) provide the core data required for all Ecological Footprint analysis worldwide.

The Accounts measure the ecological resource use and resource capacity of nations over time. Based on approximately **15,000 data points per country per year**, the Accounts calculate the Footprints of more than 200 countries, territories, and regions from 1961 to the present.

The calculations in the National Footprint and Biocapacity Accounts are based on **United Nations or UN affiliated data sets**, including those published by the Food and Agriculture Organization, **United Nations Commodity Trade Statistics Database**, and the **UN Statistics Division**, as well as the **International Energy Agency**. Supplementary data sources include studies in peer-reviewed science journals and thematic collections. Of the countries, territories, and regions analyzed in the Accounts, 150 had populations over one million and typically have more complete and reliable data sets. For most of those, Global Footprint Network is able to provide time series of both **Ecological Footprint** and **biocapacity**.

For more information about the data used to work out the national footprint and biocapacity visit: The Global Footprint Network data (link).

2.3 Methodology

2.3.1 Overview

Figures 2.2 and 2.3 show an overview of the components and calculations that comprise the National Footprint and Biocapacity Accounts.

2.3.2 Basic equations

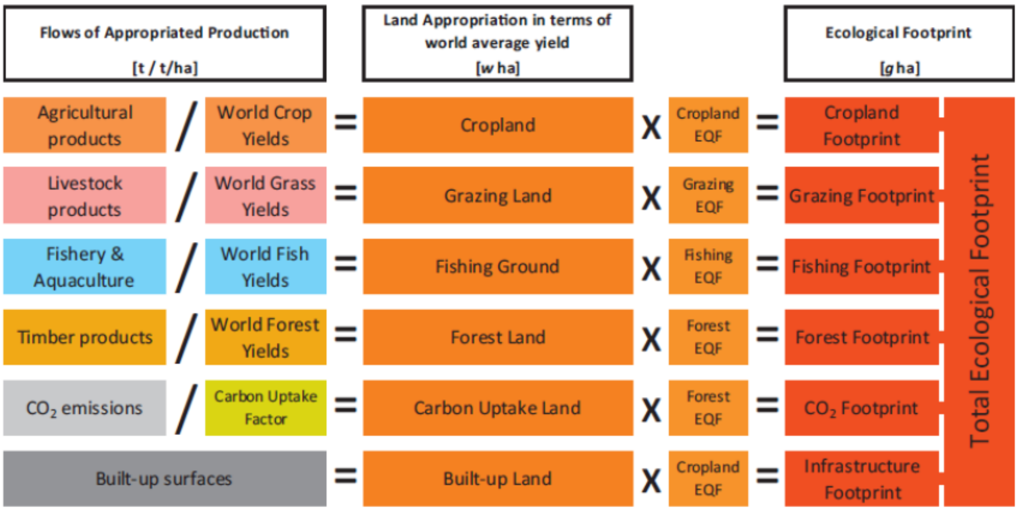
The **Ecological Footprint of consumption** is calculated as:

$$EF_{consumption} = EF_P + EF_I - EF_E \tag{2.1}$$

where:

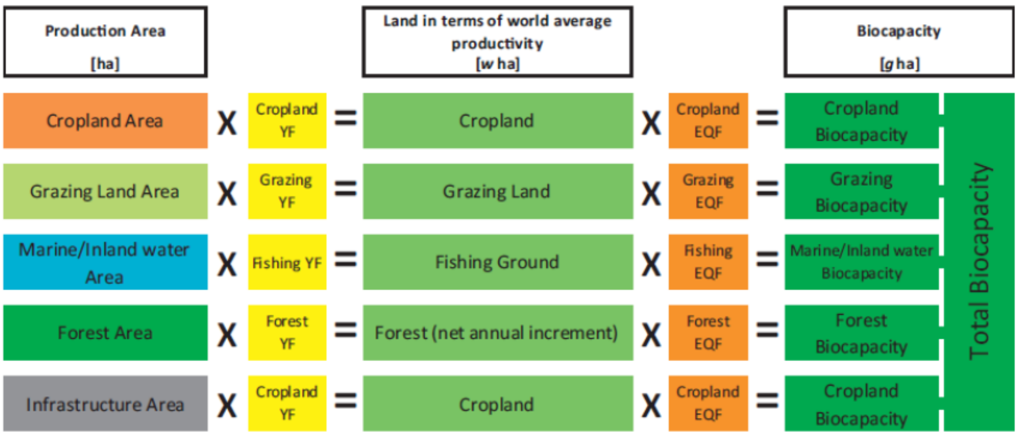
- EF_P is the is the Ecological Footprint of production,

Figure 2.2: Footprint methodology



Source: Boruckea et al.

Figure 2.3: Biocapacity methodology



Source: Boruckea et al.

- EF_I is the Ecological Footprint of imports, and
- EF_E is the Ecological Footprint of exports.

The Footprint of consumption of individual products or wastes are summed to obtain an aggregate Footprint of consumption for a given land use category. Adding together the Footprints of all of the major land use categories gives the Footprint of a country, or of the world.

Human-harvest or waste-production flow, imports, and exports are quantified in mass per time and translated into global hectares through the following equation:

$$EF_{production} = \frac{P}{Y_N} \cdot YF \cdot EQF \cdot IYF \tag{2.2}$$

where:

- $EF_{production}$ = Ecological Footprint associated with a product or waste, (gha)
- P = Amount of product extracted or waste generated, (t, yr^{-1})
- YN = National-average yield for product extraction or waste absorption, (t, nha^{-1}, yr^{-1})
- YF = Yield factor of a given land use type within a country, $(wha, nha - 1)$
- EQF = Equivalence factor for given land use type, (gha, wha^{-1})
- IYF= Intertemporal Yield factor of a given land use type, no units.

Notation:

- t: Metric tones
- nha: National-average hectares
- wha: World-average hectares
- gha: Global hectares

For each land-use type, the **EQF** is the ratio of a given land type's average global productivity divided by the average global productivity of the entire planet's productive surfaces. EQF makes it possible to compare the land used for a given product category with the average global bioproductive surface area, which may be of higher or lower average productivity.

For each country, the Ecological Footprint of production (EF_P) of a single footprint category is calculated by **summing all products of that footprint category** (such as rice, wheat, corn for cropland). The total EF_P of a country is the sum of the Ecological Footprint of all product categories combined.

Note that in Equation 2.2, because the yield factor is defined as national divided by world yield, the national-average yields cancel out. Thus, the basic Ecological Footprint formula can be expressed more succinctly in the following form:

$$EF_{production} = \frac{P}{Y_W} \cdot EQF \cdot IYF \tag{2.3}$$

where:

- Y_W = World-average yield for product extraction or waste absorption, $(t, wha - 1, yr - 1)$

Similarly, **biocapacity** can be measured in global hectares at any scale, from a single farm to the entire planet. The following formula details how biocapacity is calculated at the national level for each biocapacity land-use category:

$$BC = A_n \cdot YF \cdot IYF \cdot EQF \tag{2.4}$$

where:

- BC= biocapacity of a given land use type, (gha)
- A = Area of a given land use type within a country, (nha)
- YF = Yield factor of a given land use type within a country,$(wha, nha - 1)$
- IYF = Intertemporal Yield factor of a given land use type for that year, no units
- EQF = Equivalence factor for given land use type, $(gha, wha - 1)$

Detailed equations and their application for each of the **six Ecological Footprint subcomponents** (cropland, grazing land, fishing grounds, forest for forest products, built-up land, and carbon footprint) can be found in (Lin et al., 2019). In the next subsection, we introduce briefly those subcomponents.

Carbon

The carbon Footprint represents the area of forest land required to sequester anthropogenic carbon dioxide emissions. The National Footprint Account workbook 2019 (NFA 2019) (Lin et al., 2019) calculates the Footprint of carbon dioxide emissions using several parameters including domestic fossil fuel combustion and electricity use, embodied carbon in traded items and electricity, a country's share of global international transport emissions, and non-fossil-fuel sources.

The total amount of carbon dioxide allocated to each country is converted into global hectares based on the **Footprint intensity of carbon**. This conversion factor is derived from the following:

- the yield of the productive land that is required to absorb the carbon dioxide emissions
- the amount of carbon absorbed by oceans
- an equivalence factor for carbon as a land type
- an adjustment factor for temporal changes in yield from the forest

The International Energy Agency (IEA) tracks carbon dioxide emissions from fossil fuel combustion across 45 different economic sectors. The IEA also publishes the total world emissions in international transport in the form of International Aviation bunker fuel and International Marine bunker fuels which are aggregated to "international transport emissions." These emissions are allocated to countries according to their respective domestic fossil fuel combustion by the proportion of national to world imports. Emissions from cement are attributed to the producing country; those from gas flaring emissions are distributed based on a country's percentage of World fossil fuel consumption.

Cropland Footprint

The cropland Footprint reflects the amount of land necessary to grow all crops consumed by humans and livestock. This includes agricultural products, market animal feed, and cropped grasses used as livestock feed.

Cropland yields are calculated for each crop type by dividing the amount of crop produced by the amount of area harvested. This differs from other land use types in that yields for cropland reflect an actual harvest yield, whereas other yields are calculated based on regeneration rates. Harvest yields and regeneration rates for crops are equal by definition, as humans manage all growth on cropland for harvest.

The NFA 2019 workbook tracks the production of 177 categories of agricultural products. The list of products, including both names and codes, has been generated from a complete list of all agricultural goods included in the UN's FAOSTAT ProdSTAT database as of 2015 (FAO ProdSTAT Statistical Database).

Grazing Land Footprint

The grazing land Footprint assesses demand for grazing land to feed livestock and the embodied demand for grazing land in traded goods. This is the most logically complex section of NFA 2019. The calculations estimate the total feed requirements of all livestock produced and the percentage of livestock energy requirements derived from concentrate feeds, forage crops, and crop residues. The difference between total feed requirement and total cropped feed supply is taken to equal the demand for grazing land.

The grazing land section of NFA 2019 relies on the methodology and data proposed by Haberl et al. (2007) for calculating human appropriation of net primary production (NPP). The calculation starts with the number of livestock in a country and their feed requirements. These feed requirements are partially filled through market feed (crops grown specifically to be fed to animals), residues (crop scraps that can be fed to livestock but not to humans), and cropped grasses (grasses that are grown on cropland and cut specifically to be fed to livestock). Once the feed demand satisfied by the above sources has been accounted for, the remaining amount of feed required is assumed to be provided by grazing land. The amount of grazing land required is based on dividing the grass feed required by the average grass yield of rangeland.

Fishing Grounds Footprint

The Fishing Grounds Footprint represents the demands of fisheries on aquatic ecosystems as the equivalent surface area required to sustainably support a country's catch.

The Fishing Grounds Footprint is calculated by dividing the amount of primary production consumed by an aquatic species over its lifetime by an estimate of the harvestable primary production per hectare of marine area. This harvestable primary production is based on a global estimate of the sustainable catch of several aquatic species (Pauly and Christensen, 1995). These sustainable catch figures are converted into primary production equivalents, and divided by the total area of continental shelf. This same calculation is currently used for inland fish as well.

NFA 2019 tracks the production of 1,941 marine and freshwater species, including fish, invertebrates, mammals, and aquatic plants. The Fishing Grounds Footprint includes all wild caught fish and production through aquaculture. The complete list of species corresponds to all species tracked in FishSTAT (FAO FishSTAT Fisheries Statistical Database).

Notes:

Calculations of the yield for fish are extremely sensitive to the estimated trophic level of the species. These estimates are drawn from average values from Froese and Pauly (2016), many of which have large standard errors. The uncertainty in the fisheries yields for individual species is thus large compared to other products in NFA 2019. The yields for fish catches are calculated by estimating the amount of primary production required, given the trophic level. This calculation considers only the raw primary production available to feed marine consumers, and not the dynamics of individual marine species stocks. To the extent that particular fisheries stocks are degrading or eroding over time at the species level, this analysis may overestimate the available biocapacity of fisheries each year.

A discard rate is used to scale the yield of each species downward to reflect the discarded primary production related to their harvest. This discard rate is currently assumed to be constant across all species. This will tend to underestimate the yields for species that do not have high discard rates associated with their fisheries, and overestimate the yield for species that have higher discard rates in their fisheries (e.g., prawns). Future NFA research is looking into ways to incorporate species and geographic variability, based on new data available through SeaAroundUs.

The Footprint of production of wild fish species uses data that track the total catch landed within a country, rather than of the fish caught within the waters of that country. This differs from the definition of Footprint of production for the other land use types, where the Footprint of production refers to all products extracted from land physically located within the country. Currently, the Footprint of production calculated for fishing grounds thus cannot be compared to the biocapacity of fishing grounds for a specific country to determine whether that country's own waters are, according to world average PPR, over-fished. However, Global Footprint Network researchers are exploring ways to refine this calculation.

For more information about fisheries visit: Sea Around Us webpage (link).

Forest Products Footprint

The forest products Footprint assesses human demand for the products of the world's forests. The forest products Footprint of production is comprised of two broad types of primary product: wood used for fuel; and timber and pulp used as a raw material to produce derived wood products.

The forest products Footprint represents the area of world average forest land needed to supply wood for fuel, construction, and paper. To calculate the Footprint of forest products, timber harvests are compared against the net annual growth rates of the world's forests.

The NFA 2019 workbook tracks the production of primary forest products and products derived from them. The complete list of products has been generated from a list of all forest products included in the UN's FAOSTAT ForeSTAT database as of 2015 (FAO ForeSTAT Statistical Database). The product names and codes correspond to those used in this database.

Built-up land

The built-up land Footprint represents bioproductive land that has been physically occupied by human activities.

The NFA 2019 workbook tracks infrastructure areas required for housing, transportation, and industrial production. The calculations assume that infrastructure area covers former cropland, and apply the yield and equivalence factors for cropland to the calculation of the Footprint.

Notes.

Based on the fact that human settlements historically developed and congregated on the most agriculturally fertile land, infrastructure areas are assumed to occupy former cropland and yield and equivalence factors for cropland are thus used in the Footprint calculation. This assumption will overestimate both the Footprint and biocapacity of infrastructure areas located on areas of formerly low productivity. However, since the Footprint and biocapacity of built-up land are equal, any inaccuracies in this assumption will equally affect both. Arid countries in particular may be subject to a systematic overestimate of their infrastructure Footprint and biocapacity.

The NFA 2019 workbook does not track imports and exports of built-up land, although built-up land is embodied in goods that are traded internationally (e.g., the physical area of a factory producing a given product for export) and thus should be counted as an export of Footprint embodied in that product. This omission likely causes an overestimate of the built-up Footprint of exporting countries, and an underestimate of the built-up Footprint of importing countries.

Since low-resolution satellite images are not able to capture dispersed infrastructure such as roads and houses, estimates of infrastructure areas have high levels of uncertainty. The NFA 2019 workbook likely underestimates the actual extent of impermeable surfaces overlaying productive land.

Biocapacity

Biocapacity refers to the amount of biologically productive land and water areas available within the boundaries of a given country. Biocapacity is calculated for each of the five major land use types: cropland, grazing land, fishing grounds (marine and inland waters), forest, and built-up land. Built-up land biocapacity is included here because, though built-up land does not generate resources, buildings and infrastructure occupy the biocapacity of the land they cover. The carbon Footprint does not have corresponding biocapacity because NFA 2019 assumes all carbon uptake as a demand on forest land biocapacity. Therefore, including carbon dioxide biocapacity in addition to forest land biocapacity would lead to double counting.

Notes.

There is no biocapacity figure for carbon uptake. All other land use types have a corresponding biocapacity calculation. Biocapacity for cropland is equal to the cropland Footprint of production because the yields are defined by human use.

Yield Factors

Yield factors reflect the relative productivity of national and world average hectares of a given land use type. Each country, in each year, has a yield factor for each land use type. Yield factors are used in biocapacity calculations when biocapacity is reported in global hectares. For land use types for which there are data on the average growth for primary production, yield factors are calculated using Equation 2.5 (Yield Factors Simple Calculation). This equation applies to grazing land, fishing grounds, and forest.

$$YF_N^L = \frac{Y_N^L}{Y_W^L} \tag{2.5}$$

where:

- YF_N^L = Yield factor for a given country and land use type, $(wha, nha-1)$
- Y_N^L = Yield for a given country and land use type, $(t, nha-1)$
- Y_W^L = World-average yield for a given land use type, $(t, wha-1)$

Cropland produces more than one primary product. For this land use type, equation 2.6 (Yield Factors Extended Calculation) is used.

$$\begin{aligned} YF_N^L &= \frac{\sum A_W}{\sum A_N}, \text{ where} \\ A_N &= \frac{P_N}{Y_N}, \text{ and} \\ A_W &= \frac{P_W}{Y_W} \end{aligned} \tag{2.6}$$

where:

- YF_N^L =Yield factor for a given country and land use type, $(wha, nha-1)$
- A_N = Area harvested for a given quantity of product in a given country, $(nha-1)$
- A_W = Area that would be required to produce a given quantity of product using world average land, $(wha-1)$
- P_N = Amount of given product extracted or waste generated in a country, $(t, yr-1)$
- Y_N = National yield for product extraction, $(t, nha-1, yr-1)$
- Y_W = World-average yield for product extraction, $(t, wha-1, yr-1)$

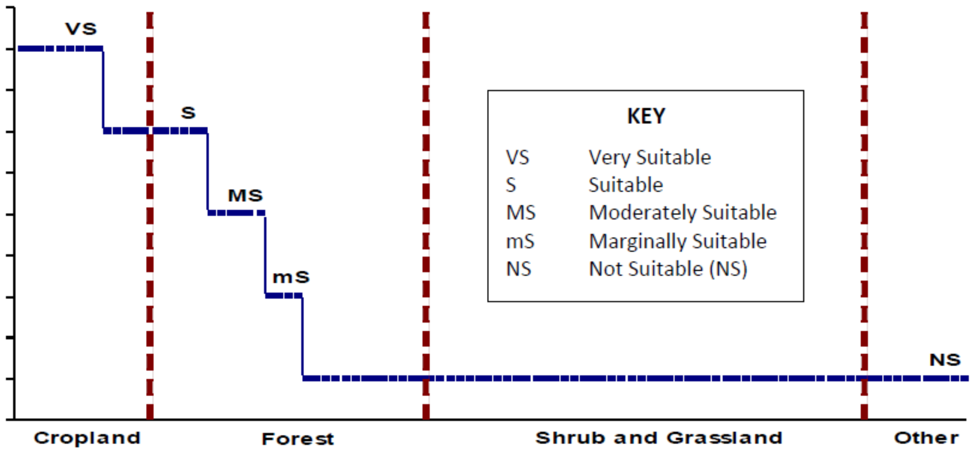
Equivalence Factors

Equivalence factors reflect the relative productivity of world average hectares of different land use types. Equivalence factors are the same for all countries, and change slightly from year to year. Equivalence factors are calculated in a satellite workbook to the NFA 2019 which is available upon request.

Equivalence factors are calculated using suitability indexes from the Global Agro-Ecological Zones (GAEZ) model, combined with information about actual areas of cropland, forest, and grazing area from FAOSTAT (Global Agro-Ecological Zones 2000; FAO ResourceSTAT Statistical Database). The GAEZ model divides all land globally into five categories, each of which is assigned a suitability score:

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

Figure 2.4: Equivalence factors



Source: Lin et al. (2019)

The equivalence factor calculation assumes that the most productive land is put to its most productive use. The calculations assume that the most suitable land available will be planted to cropland, the next most suitable land will be under forest, and the least suitable land will be grazing area. The equivalence factor is calculated as the ratio of the average suitability index for a given land use type divided by the average suitability index for all land use types.

The equivalence factor for built up area is set equal to the equivalence factor for cropland, reflecting the assumption that built up areas occupy former cropland.

The equivalence factor for marine area is calculated such that a single global hectare of pasture will produce an amount of calories of beef equal to the amount of calories of salmon that can be produced on a single global hectare of marine area. The equivalence factor for inland water is set equal to the equivalence factor for marine area.

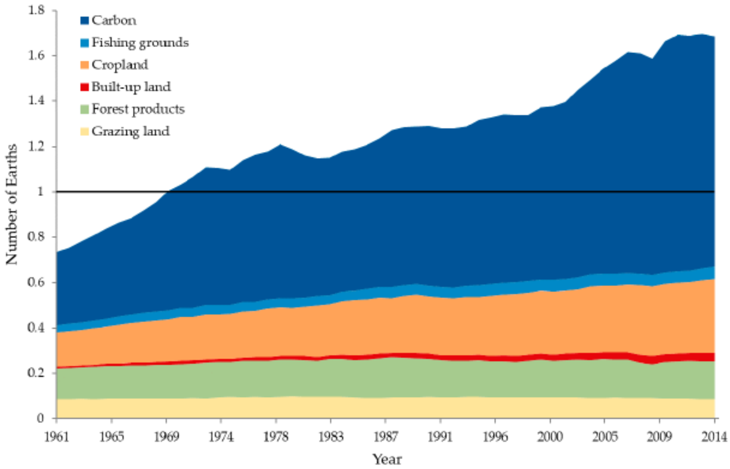
For more information about the Global Agro-Ecological Zones (GAEZ) model visit: GAEZ model webpage (link).

2.3.3 The accounting principles are:

- **Additivity:** Given that human life competes for biologically productive surfaces, these surface areas can be summed.
- **Equivalence:** Biologically productive areas vary in their ability to produce biological flows (i.e., biological resources and services used by people). Therefore, areas are scaled proportionally to their biological productivity.

Using these principles, Ecological Footprint accounting tracks the **supply (biocapacity)** and **demand (Ecological Footprint)** of renewable resources and ecosystem services. The expression of biological flows as **global hectares** allows for direct comparisons between them, making it possible to quantify human demand on the biosphere.

Figure 2.5: Footprint global trends



Source: Lin et al. (2018)

2.4 Analysis

<u>Global trends:</u>

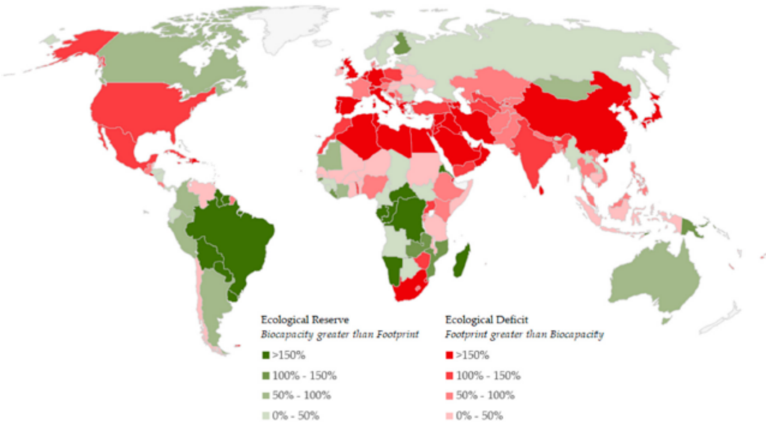
Humanity's total **Ecological Footprint** has been increasing steadily at an average of 2.1 percent per year (SD = 1.9) since 1961, nearly tripling from 7.0 billion gha in 1961 to 20.6 billion gha in 2014. The increase in Ecological Footprint has been **outpacing biocapacity** increases, which have increased at an average of 0.5 percent per year (SD = 0.7), from 9.6 billion gha in 1961 to 12.2 billion gha in 2014. Together, these results indicate that Earth's ecological overshoot began in the 1970s; further, ecological overshoot continues to grow at an average rate of 2.0 percent (SD = 2.3) per year. In 2014, humanity's Ecological Footprint was 69.6 percent greater than Earth's biocapacity.

During the same period, **per capita Ecological Footprint** increased by 24 percent (2.29 to 2.84 gha per person), while **per capita biocapacity** decreased by 46 percent (3.13 to 1.68 gha per person). The increase in total biocapacity and decrease in per capita biocapacity are indicative of a growing global population. More recently, the world Ecological Footprint per person decreased by 1.1 percent between 2010 and 2014, while biocapacity per person decreased by 2.4 percent over the same time period. In other words, although our individual share of the world's biocapacity is decreasing, we are also reducing our individual demand on nature.

The **carbon footprint** is the fastest growing Footprint component; in 2014, it comprised 60 percent of the world's total Ecological Footprint. This is a significant increase from the carbon Footprint in 1961, which contributed to 44 percent of the world's Ecological Footprint, or 150 years ago, when it was less than one percent of what it is today (figure 2.5). **Cropland footprint** was the next largest contributor to the world's Ecological Footprint in 2014, at 19.4 percent, followed by **forest-product** (9.8 percent), **grazing-land** (5.1 percent), **fishing-ground** (3.3 percent), and **built-up-land** (2.3 percent) Footprint types (figure 2.5).

Across **individual countries**, results show that most countries run a biocapacity deficit, where they have larger Ecological Footprints than biocapacity (figure 2.6). Countries that continue to have biocapacity reserves (where the biocapacity within a country's borders is greater than the Ecological Footprint of that country) tend to be located in forested regions, such as the

Figure 2.6: Ecological deficit and reserves



Source: Lin et al. (2018)

tropics and boreal latitudes.

<u>Sustainable development trends.</u>

National progress towards sustainable development can be assessed by comparing the NFA results to the United Nations' **Human Development Index (HDI)**, which aggregates education, longevity, and income into a single metric (figure 2.7).

The United Nations Development Program (UNDP) defines an **HDI score of 0.7 as the threshold for high development**. The **biocapacity available on the planet is calculated as 1.7 gha per person**. Combining these two thresholds gives clear minimum conditions for globally sustainable human development. Countries in the light-blue section of the lower right-hand box (figure 2.7) exhibit high levels of development with globally replicable resource demand. As of 2014, only two countries fit these criteria: Sri Lanka and the Dominican Republic. On average, the world is moving closer to the Global Sustainable Development Quadrant: HDI has increased consistently since the metric was developed in 1990, from 0.55 in 1990 to 0.69 in 2014 (weighted by the population of each country). In addition, the world's Ecological Footprint per person decreased from slightly from 2013 to 2014. However, the current world Ecological Footprint of 2.8 gha per person remains far above the 1.7 gha of biocapacity available to each person.

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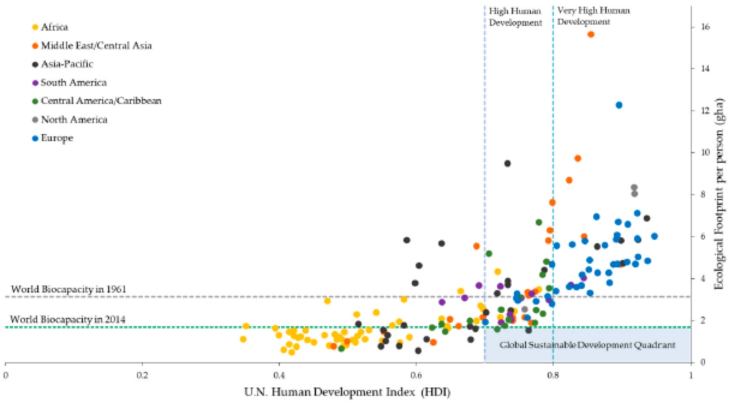
Figure 2.7: Sustainable development



Source: Lin et al. (2018)

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