Lecture 02
Indicators

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CIVIL-239: Engineering a sustainable built environment

17 September 2025

Housekeeping

- Assignment 1: Due next week

Outline

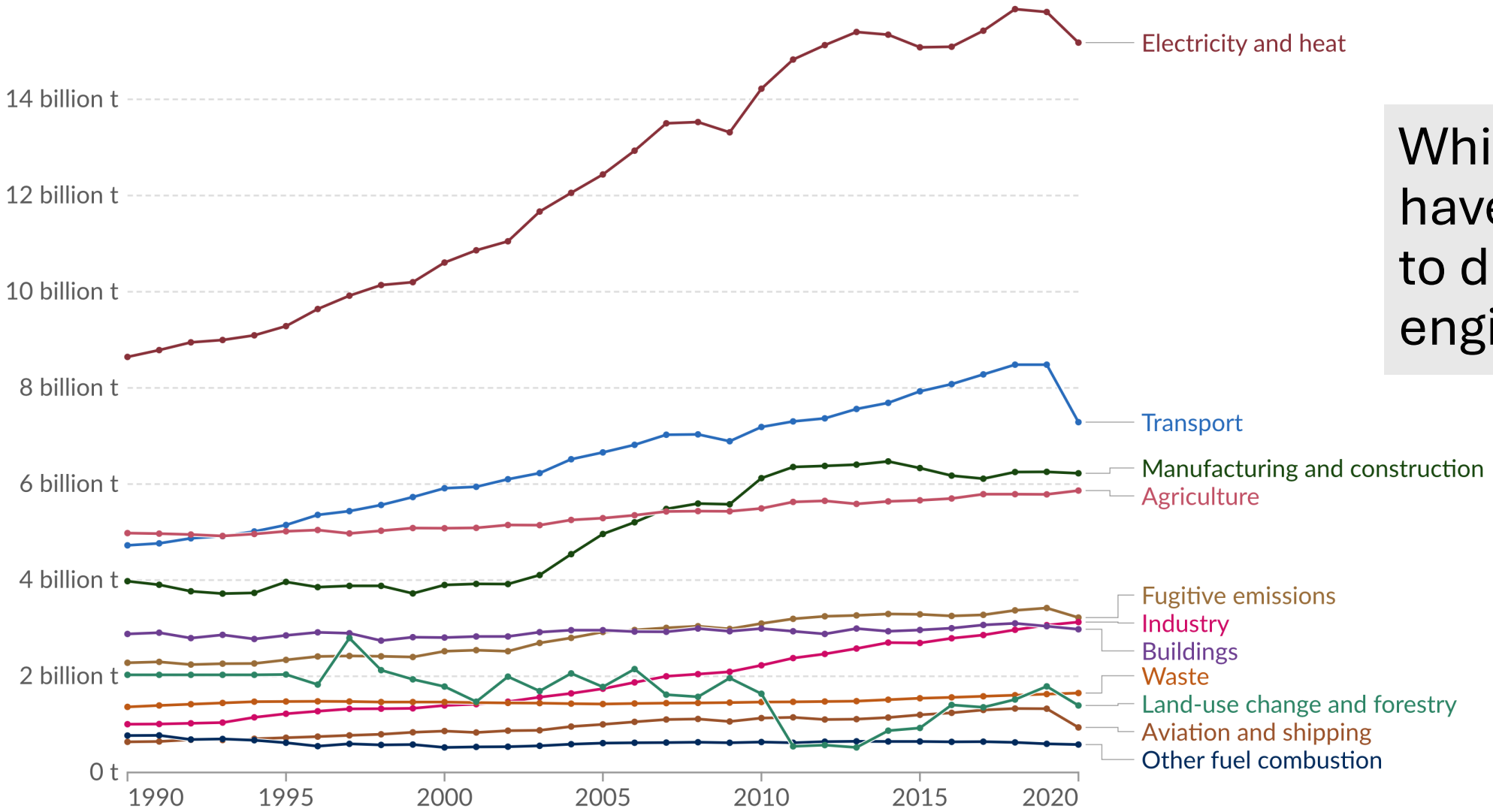
- Wrap up sustainability in civil engineering intro
- How we have measured the state of the planet so far
- How do we measure the performance of our society?
- How do we measure well-being and sustainability?
  - Foundational measure: GDP
  - Beyond GDP
- Human Development Index
- Inequality Index (GINI coefficient)
- Ecological footprints (balancing society's demands on the planet with the Earth's capacity)

Sustainability in civil engineering

Greenhouse gas emissions by sector, World

Greenhouse gas emissions[1] are measured in tonnes of carbon dioxide-equivalents[2] over a 100-year timescale.

Our World in Data



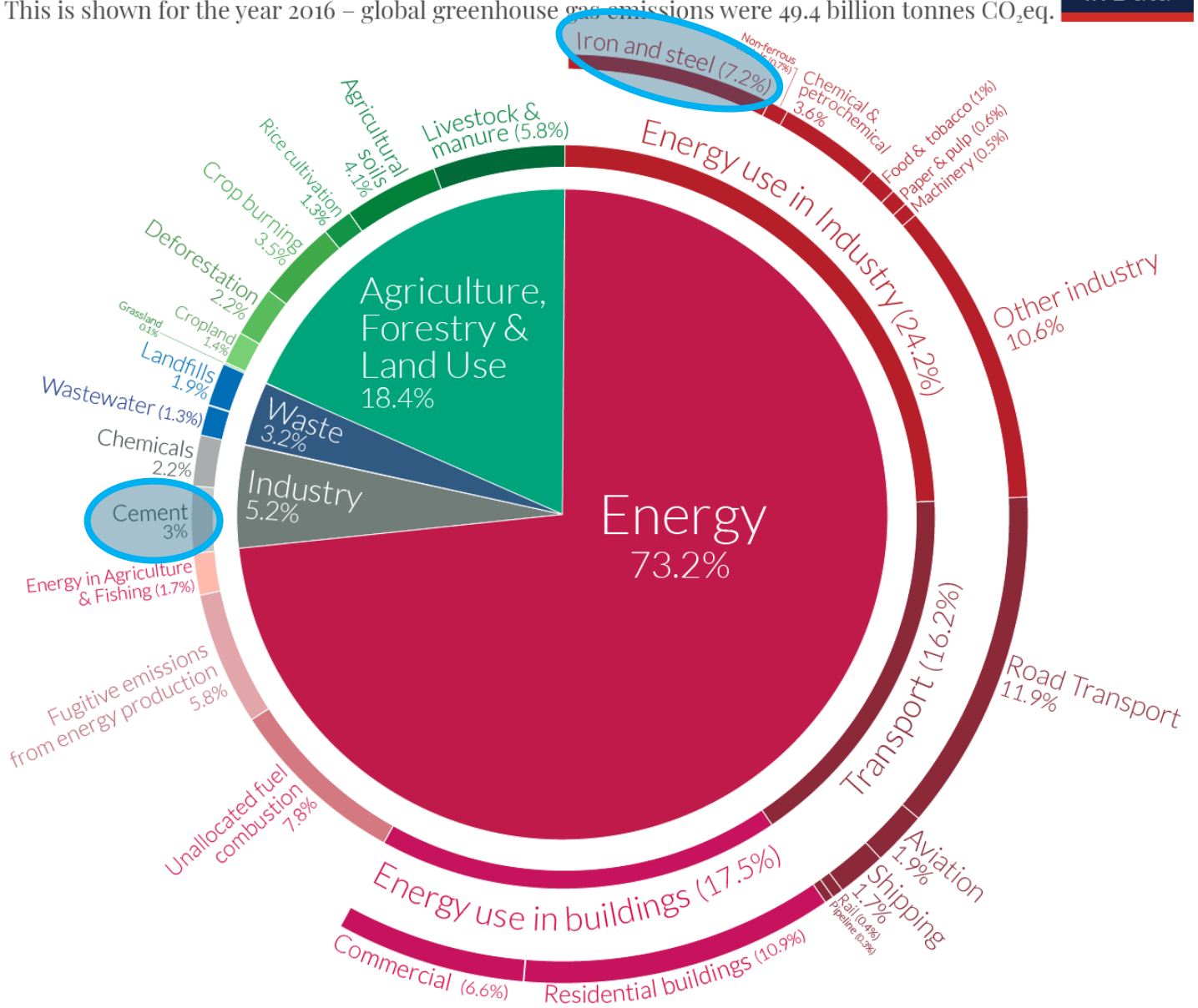
Which of these have something to do with civil engineering?

Data source: Climate Watch (2023)
Note: Land-use change emissions can be negative.

OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

Another way to visualize (but note data is from 2015)

- Direct CO2 emissions from electricity production ~40% of total
- Cement and steel production



UN Sustainable Development Goals (SDGs)

Directly related to civil engineering

Overview of the topics in this course

- Part 1 – Course introduction, the climate crisis, setting the scene
- Part 2 – Buildings, energy demand, and energy supply
- Part 3 – Mobility and sustainability
- Part 4 – Materials, structures, and life-cycle assessment
- Part 5 – Natural systems and natural capital
- Part 6 – Sustainability in practice (guest lecture from industry)

Our task for today

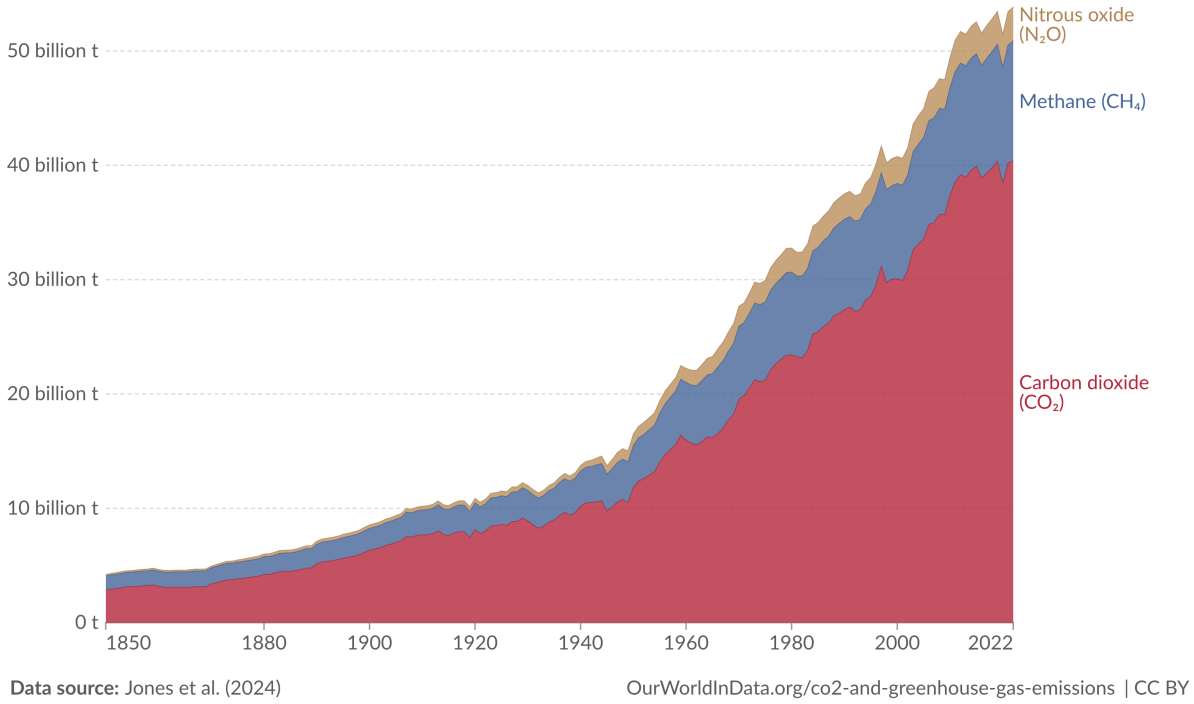
- We are going to be talking a bit about economics
- We need to generate an understanding of what drives our activities as a society
- What we value and how we achieve it is fundamental to the provision of the built environment
- We are also going to talk about other ways to measure the performance of our society
- **What isn’t measured can’t be managed**

I believe that the climate crisis is the single greatest challenge that my generation faces

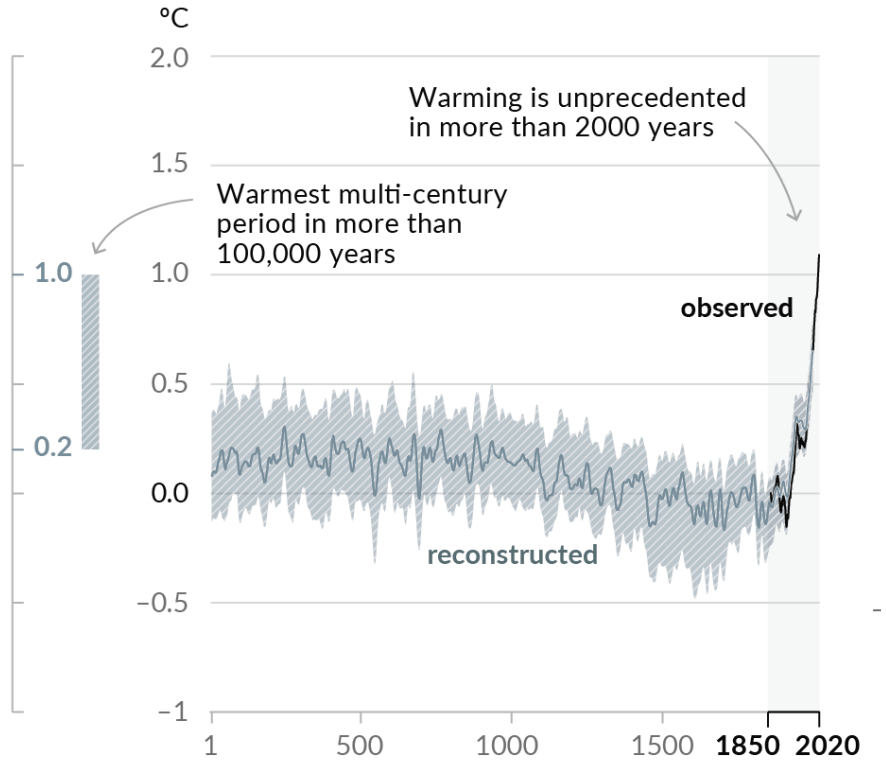
A. True
B. False

Measuring the state of the planet (so far)

Emissions

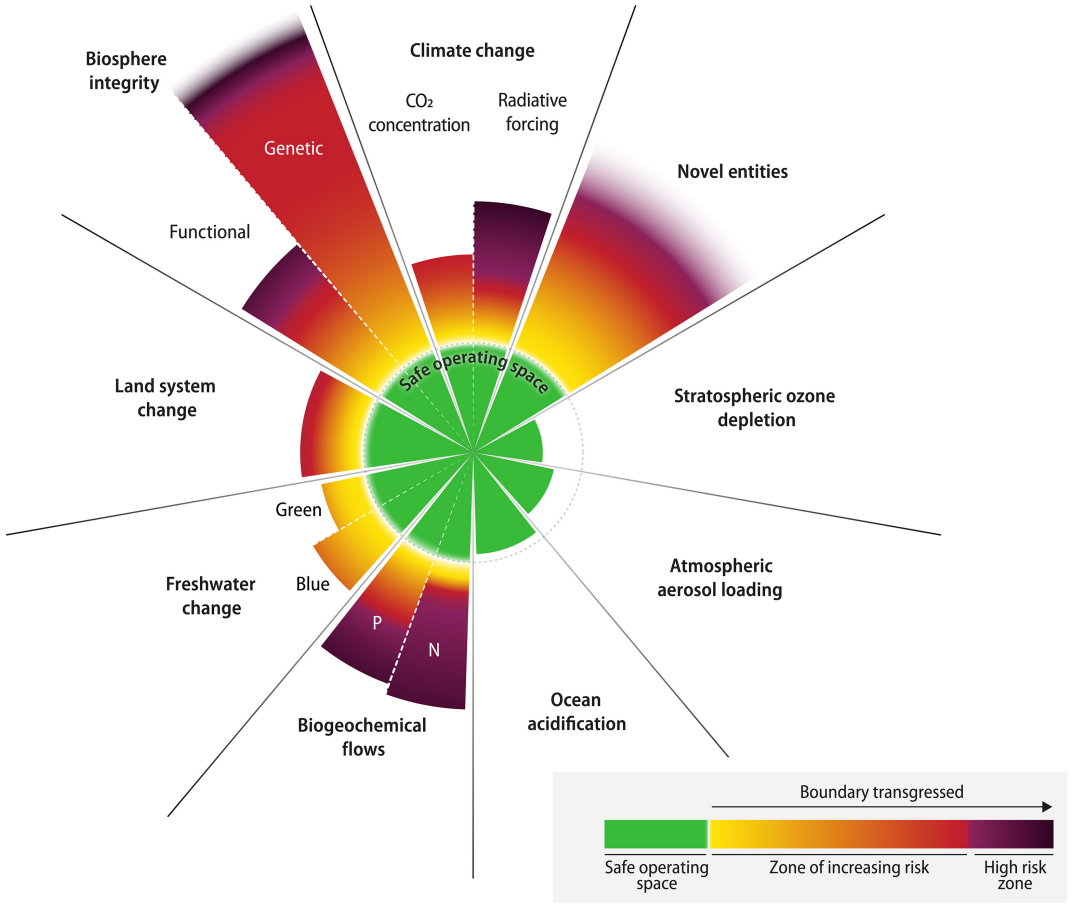


Temperature

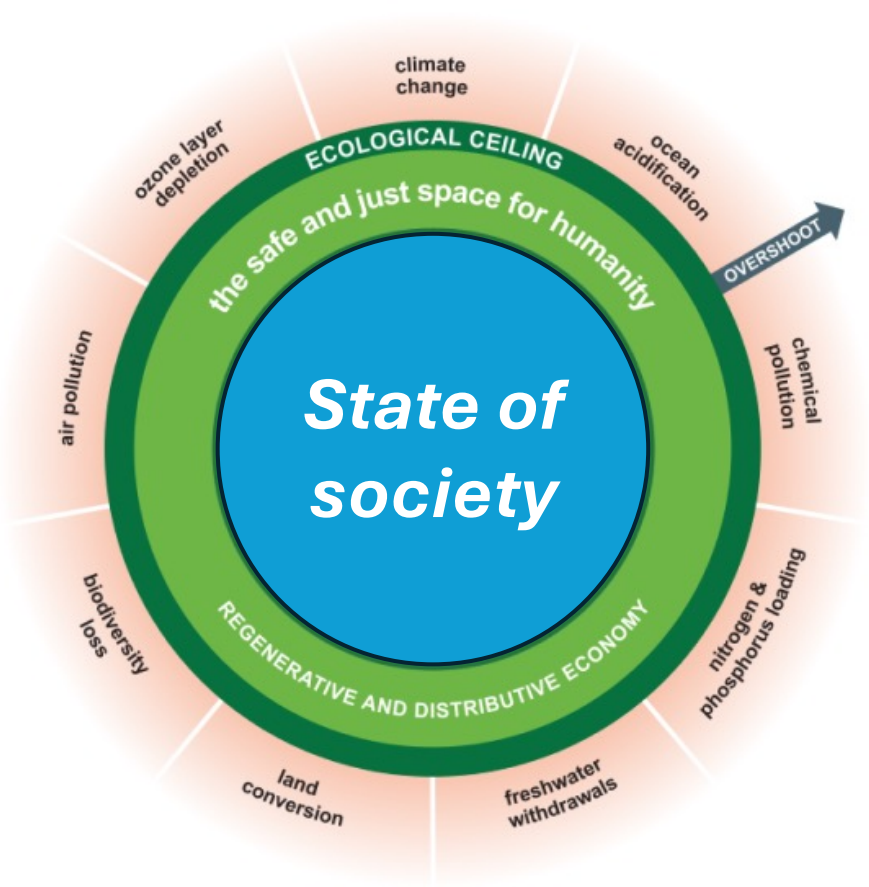


Measuring the state of the planet (so far)

Planetary boundaries



Doughnut model



How do we measure the performance of our society?

- Take yourself to an era of limited data and digital tools
- In the 1920s…

In the 1930s…

How do we measure the performance of our society?

- Simon Kuznets, a Russian-born US economist, had an idea:
- Calculate the monetary value of goods and services produced in a country over a given period (usually a year)
- This is GDP! Two ways to calculate:
  - aggregate all monetized economic activities
  - aggregate all income distributed in an economy (profits, wages, and taxes)
- Macroeconomics 101: GDP = C + I + G + X – M
  - C: consumption
  - I: investment
  - G: government spending
  - X: exports
  - M: imports

What does GDP tell us?

- Total economic output (GDP)
- Standard of living (GDP per capita)
- Economic development (growth in GDP per capita)
- Growth (growth in GDP)
- GDP is a benchmark

What does GDP ***not*** tell us?

- GDP was designed during a time when industrial growth and quest for material wealth were primary drivers for society
- Little concern for planetary health at the time
- General problem: GDP is appropriate for market goods and services that can be **valued at their market price**
  - True costs are not always indicated in market price (who pays for destructive impact of carbon emissions?)
- Even more problematic: GDP positively values a number of “counterproductive” expenditures:
  - Incarceration
  - Oil spills
- GDP does not consider our experience of well-being
- Bobby Kennedy, US Senator, 1968: "measures neither our wit nor our courage, neither our wisdom nor our learning, neither our compassion nor our devotion to our country, it measures everything in short, except that which makes life worthwhile

What are the problems with GDP?

- It is the main driver of economic policy around the world
- Increasing GDP does not necessarily increase our well-being or the sustainability of the Earth
  - Well-being: less concern for equality/wealth distribution that simply increasing GDP
  - Sustainability: short term gains in GDP can make politicians look good, even at the cost of environmental damage

Beyond GDP

- What matters for people and their experiences are becoming more and more disconnected from GDP
- Environmental sustainability is not at all accounted for

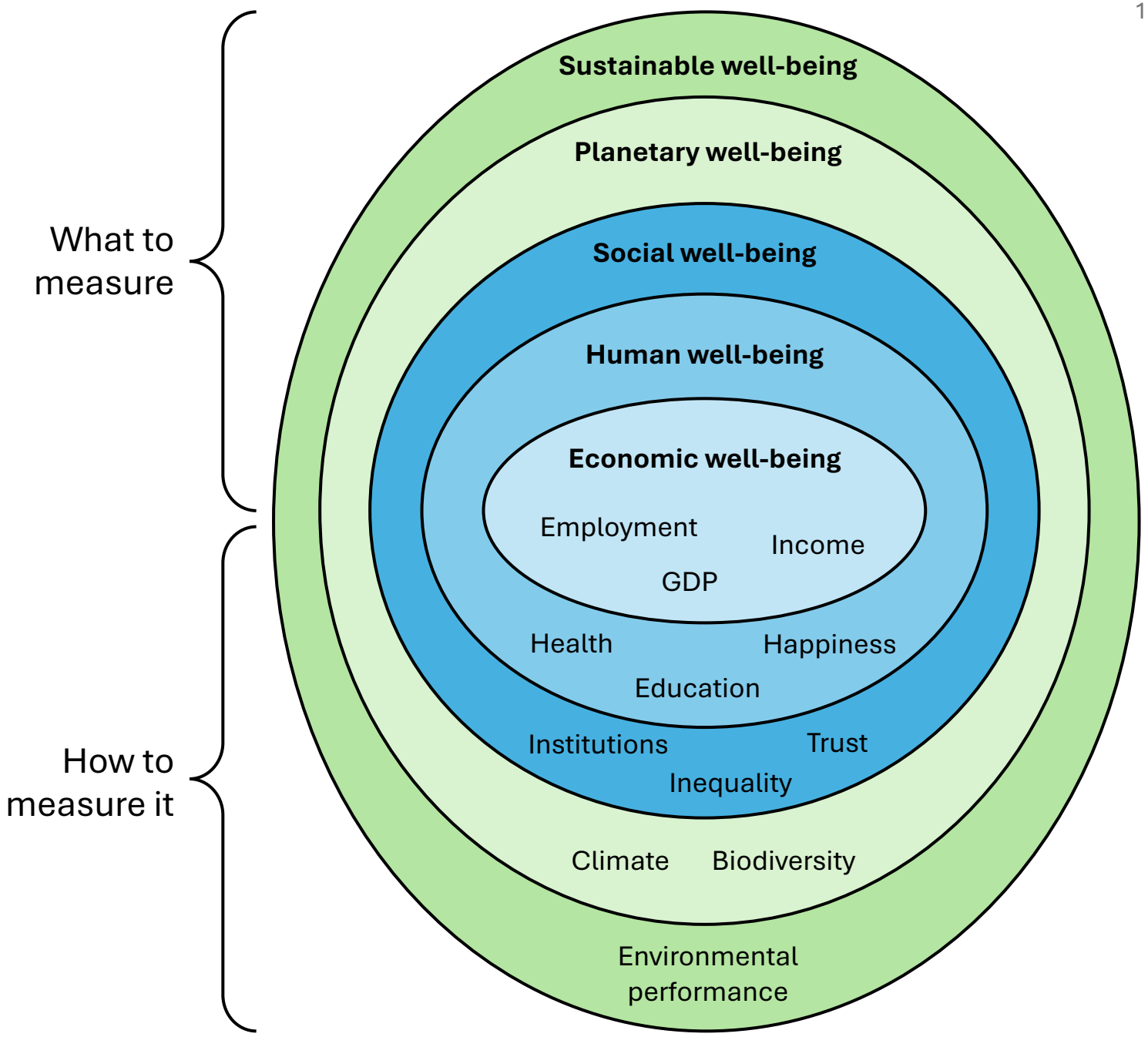
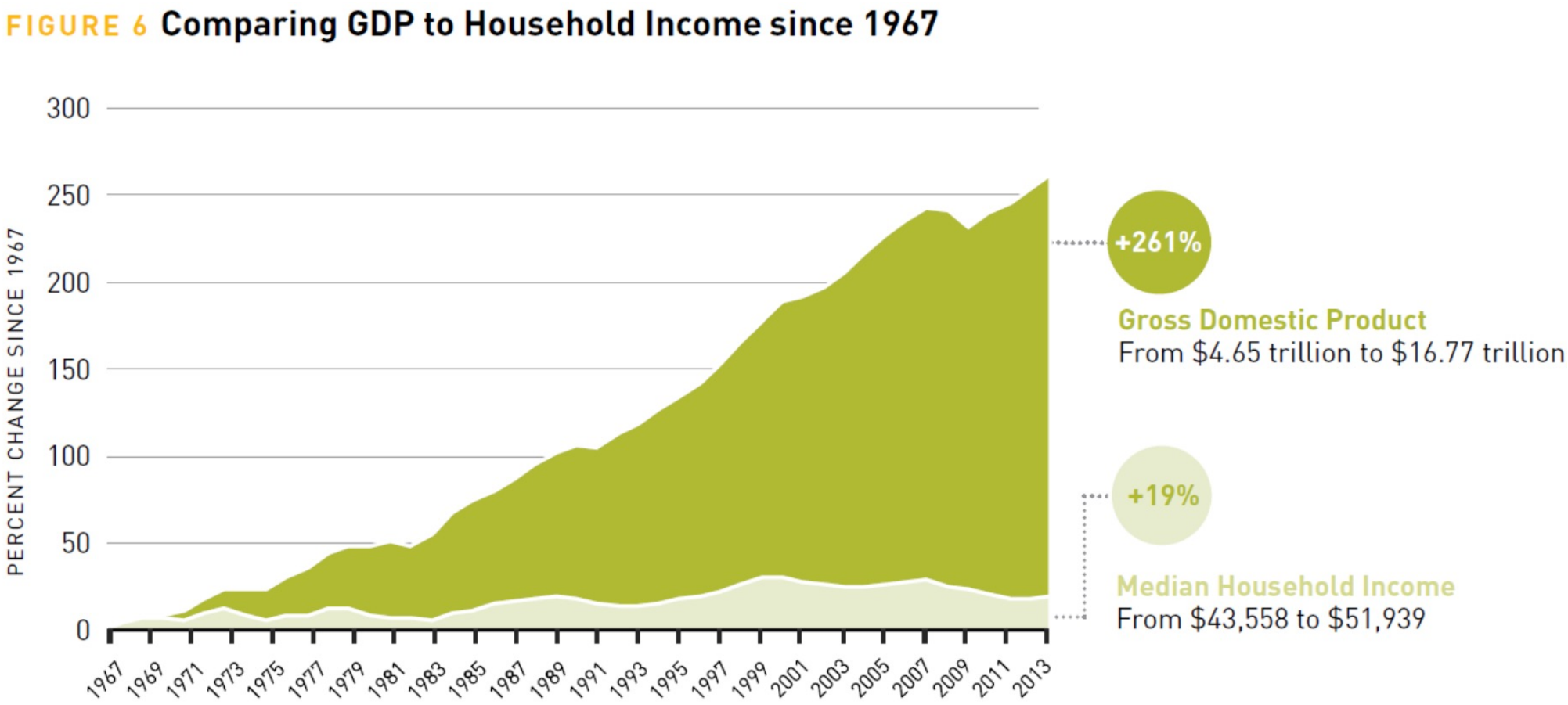


Image credit: Eloi Laurent, Sciences Po

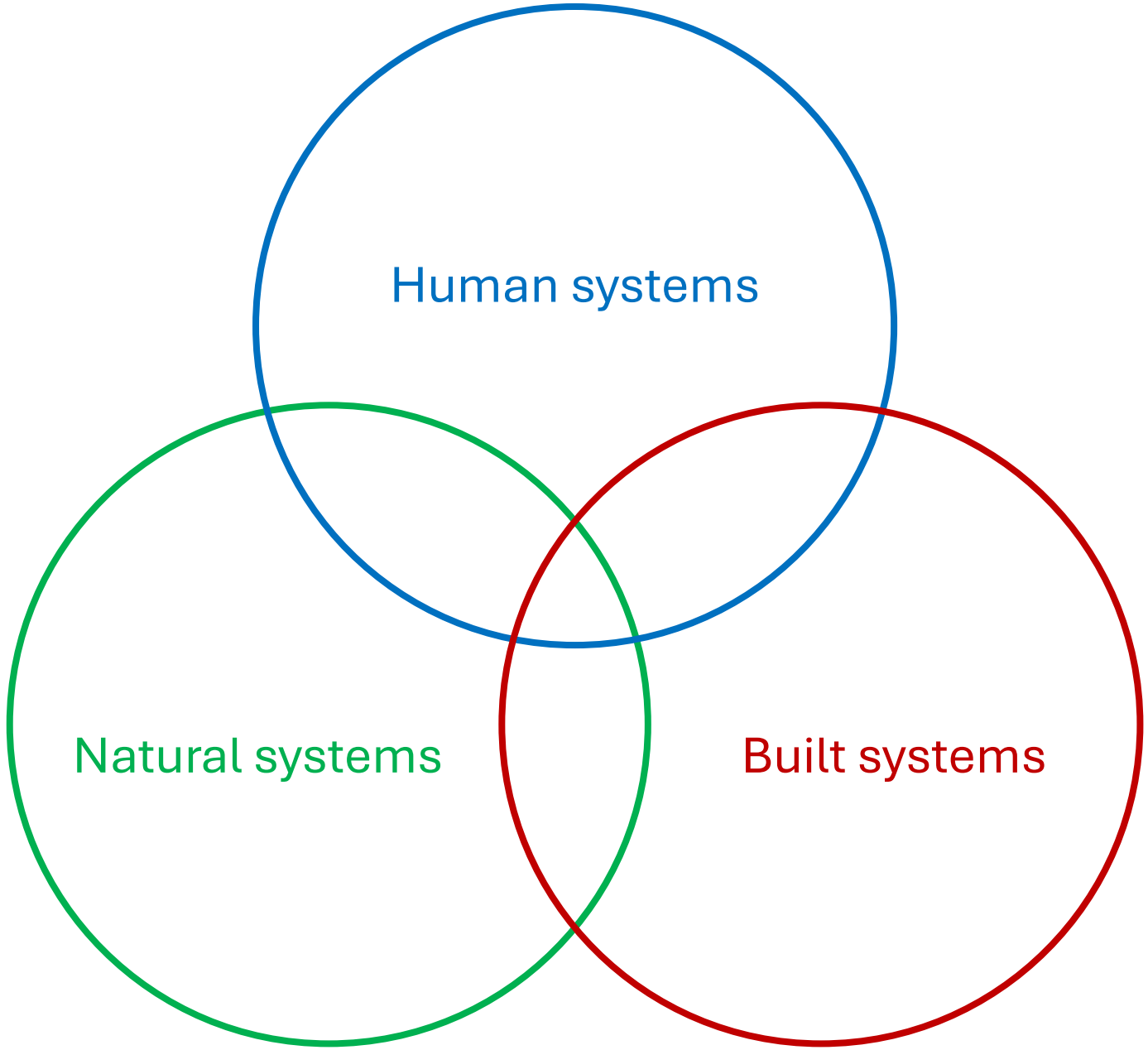
GDP and income



Growth vs. Sufficiency

- Growth mindset: economic **growth** improves our well-being
- Sufficiency mindset: there is a certain level of economic activity that is **sufficient for a good life**
  - Seeking enough when more is possible
- UN Intergovernmental Panel on Climate Change (IPCC) definition of sufficiency:
  "a set of **policy measures** and **daily practices** that avoid the demand for energy, materials, land, water, and other natural resources while **providing wellbeing for all within the planetary boundaries**"

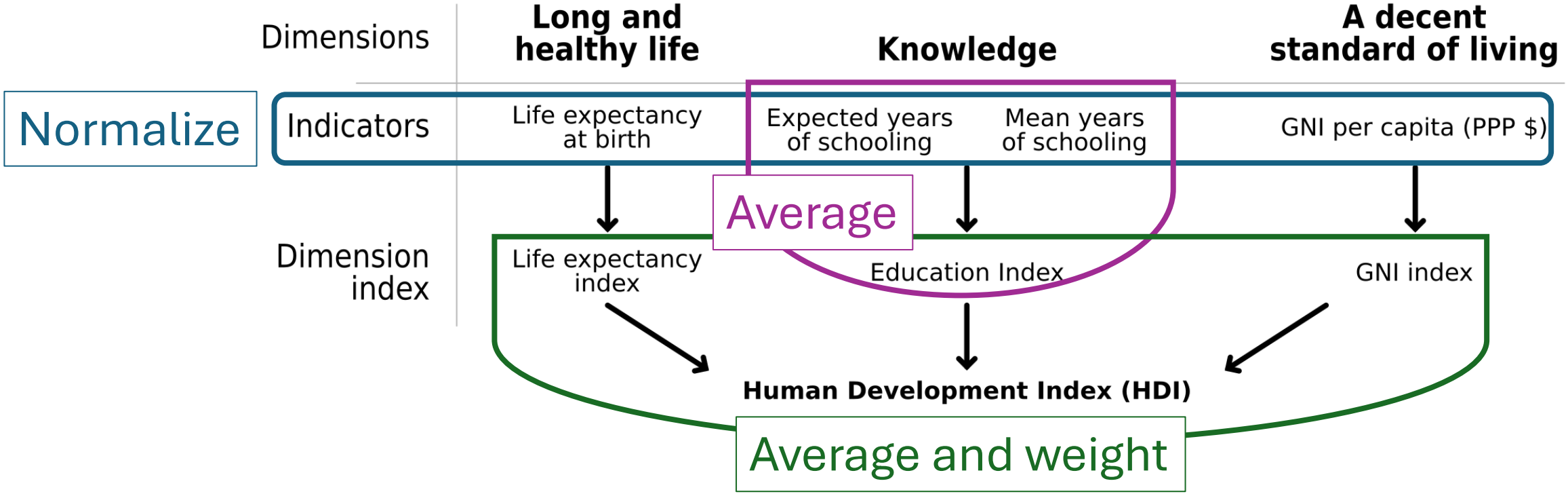
What systems exist in cities… and how can we measure their performance?



Human Development Index

- The Human Development Index (HDI) is an example of a **composite** indicator
- Based on work of Amartya Sen (Harvard Economist): human development is defined as a process of enlarging people's **choices** and enhancing human **capabilities**
- Developed by Mahbub ul Haq (United Nations Development Program)
- Intention: shift focus from income of a nation to **people-centered policies**

Constructing the HDI (composite index)



Source: Wikimedia commons

Constructing the HDI: Normalizing

"No country in the 20th century had a life expectancy at birth of less than 20 years"

"Societies can subsist without formal education, justifying the education minimum of 0 years"

Dimension	Indicator	Minimum	Maximum
Health	Life expectancy at birth (years)	20	85
Education	Expected years of schooling (years)	0	18
	Mean years of schooling (years)	0	15
Standard of living	GNI per capita (2017 PPP$)	100	75,000

Master's degree

Projected max for 2025

Values above this don't contribute to HDI

Source: UN HDP Technical Notes

Constructing the HDI: Normalizing

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$$\text{Dimension index} = \frac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$

(Also apply rule that dimension index can't be greater than 1)

* For standard of living (GNI/capita) apply **natural log** to all values

Source: UN HDP Technical Notes

Constructing the HDI: Combining indices

- The HDI is the **geometric mean** of the 3 dimensional indices

$$HDI = (I_{Health} \cdot I_{Education} \cdot I_{Income})^{1/3}$$

Calculating the HDI: Example of Pakistan

$$\text{Dimension index} = \frac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$

Dimension	Indicator	Minimum	Maximum	Value	Dimension Index
Health	Life expectancy at birth (years)	20	85	66.4	
Education	Expected years of schooling (years)	0	18	7.9	
	Mean years of schooling (years)	0	15	4.4	
Standard of living	GNI per capita (2017 PPP$)	100	75,000	5374	0.602

What is the HDI of Pakistan?

$$\text{Dimension index} = \frac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$

Dimension	Indicator	Minimum	Maximum	Value	Dimension Index
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Standard of living	GNI per capita (2017 PPP$)	100	75,000	5374	0.602

A. 0.174
B. 0.540
C. 0.561
D. 0.654

responseware.eu
Session ID: ethos

What would be the HDI if the simple (arithmetic) mean were used?

$$\text{Dimension index} = \frac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$

Minimum	Maximum	Value	Dimension Index
20	85	66.4	
0	18	7.9	
0	15	4.4	
100	75,000	5374	0.602

A. 0.174
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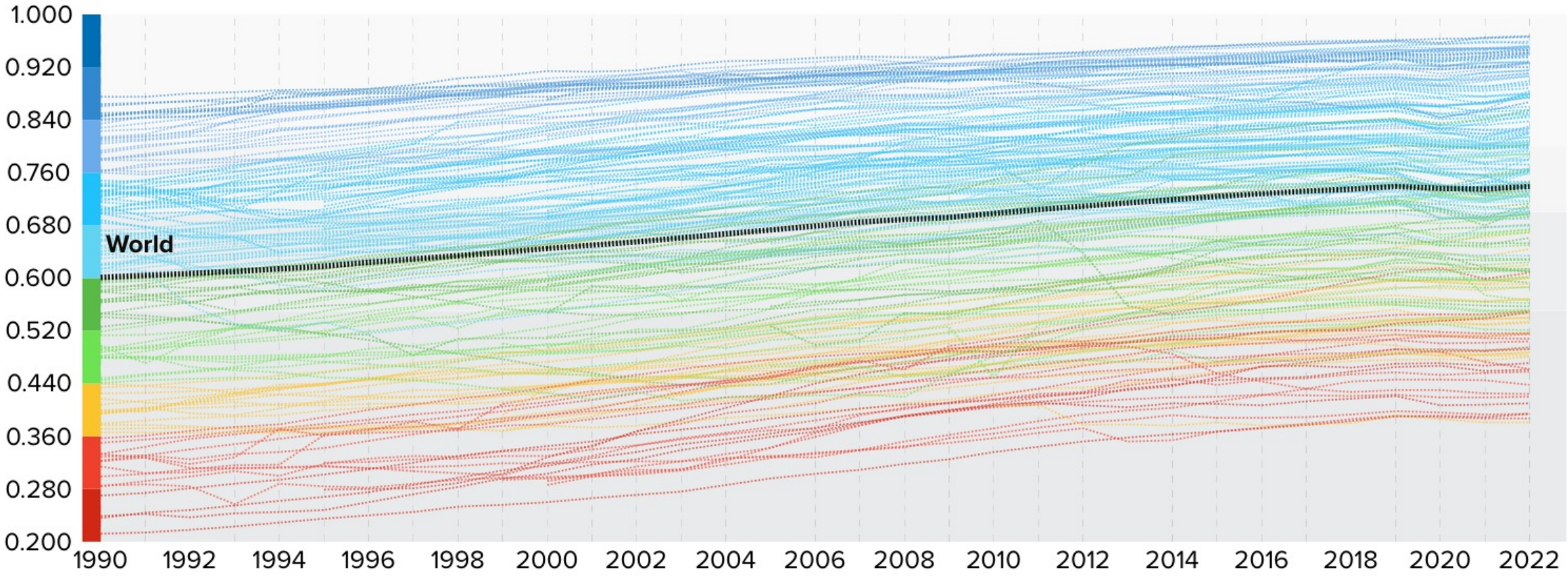
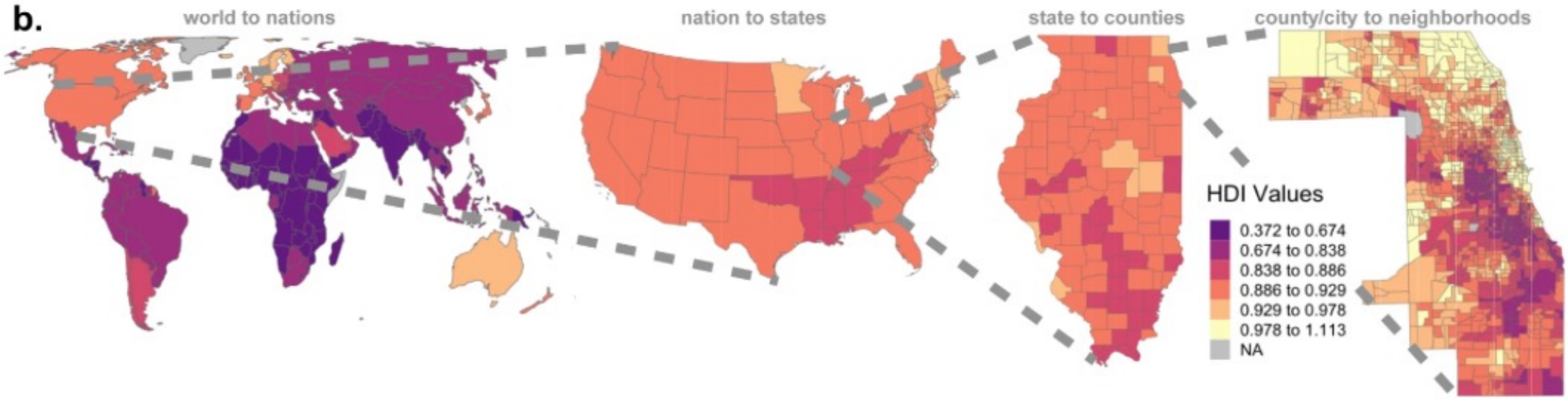
HDI over time

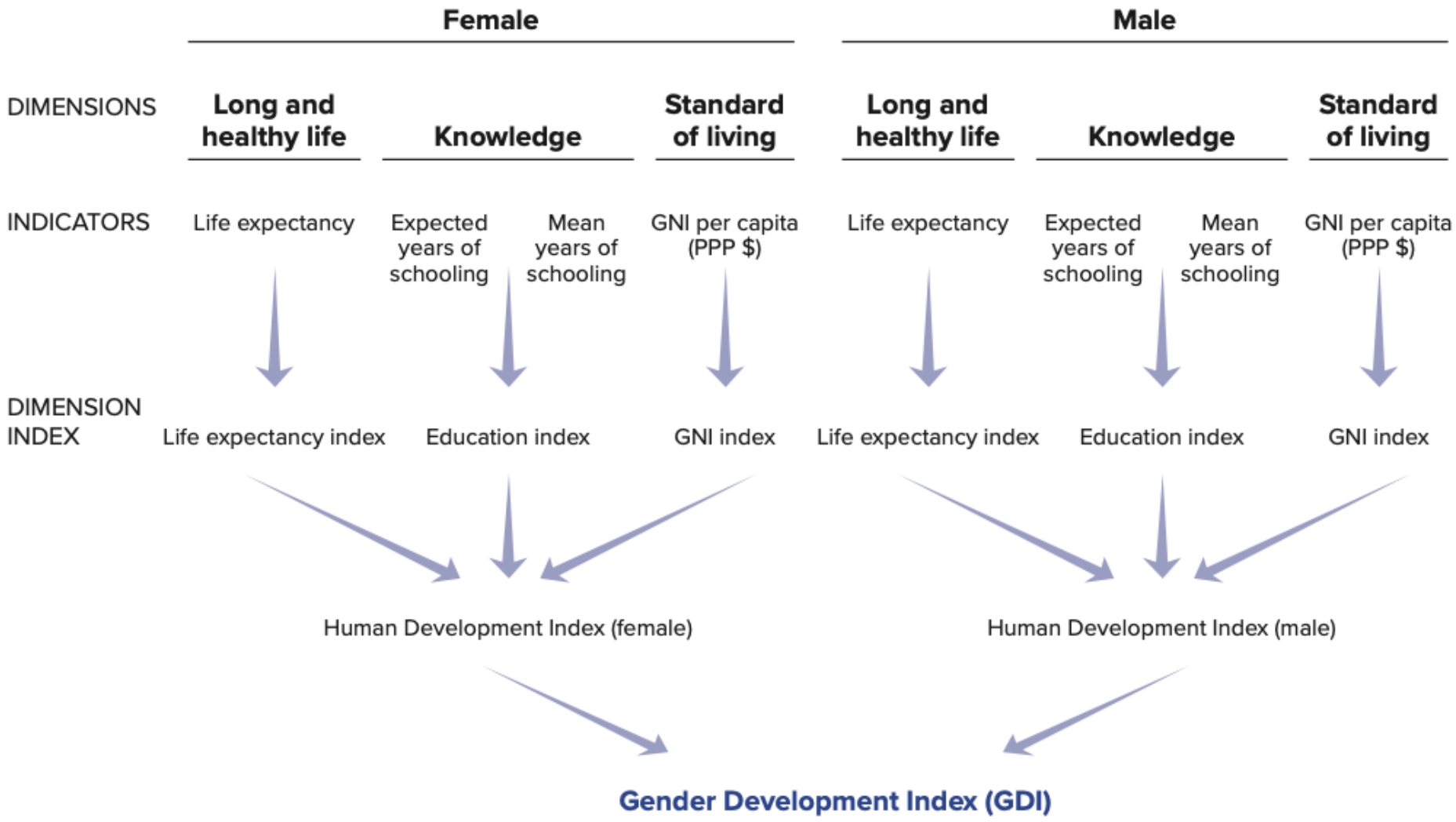


HDI and spatial resolution

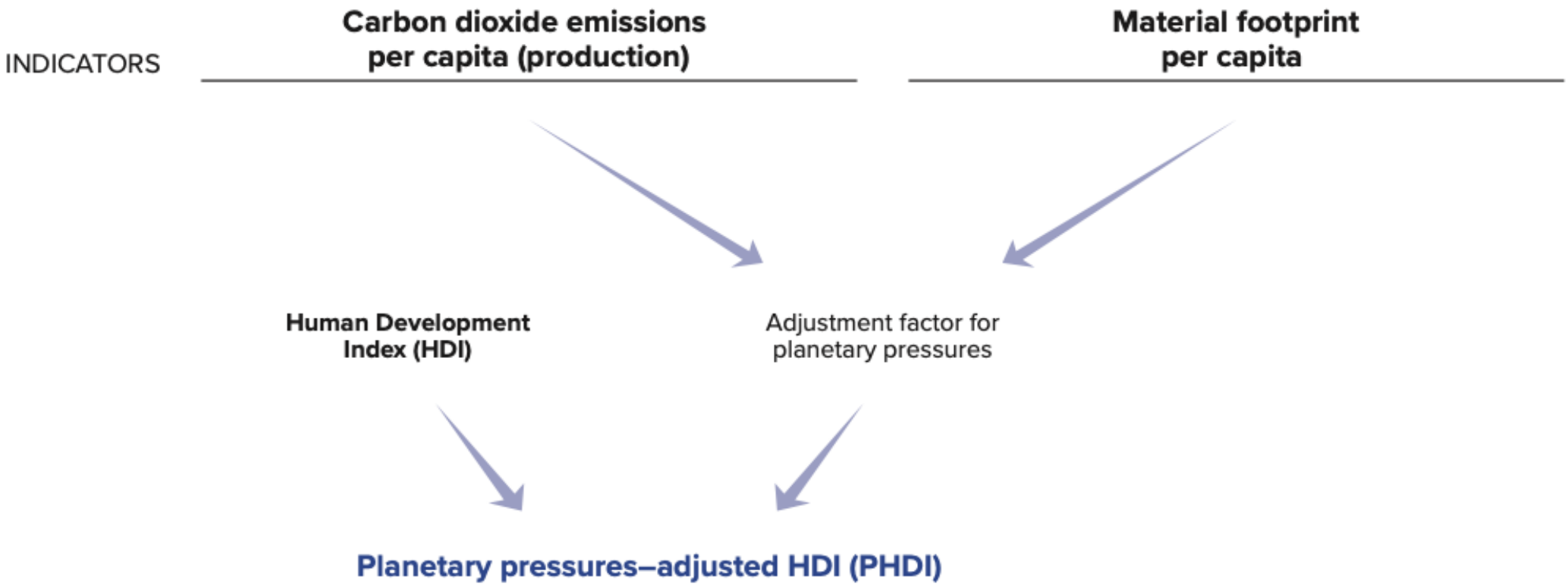


Sheth, S.K., Bettencourt, L.M.A. Measuring health and human development in cities and neighborhoods in the United States. *npj Urban Sustain* **3**, 7 (2023). https://doi.org/10.1038/s42949-023-00088-y

Extensions of HDI (Gender)



Extensions of HDI (Planetary Pressures)

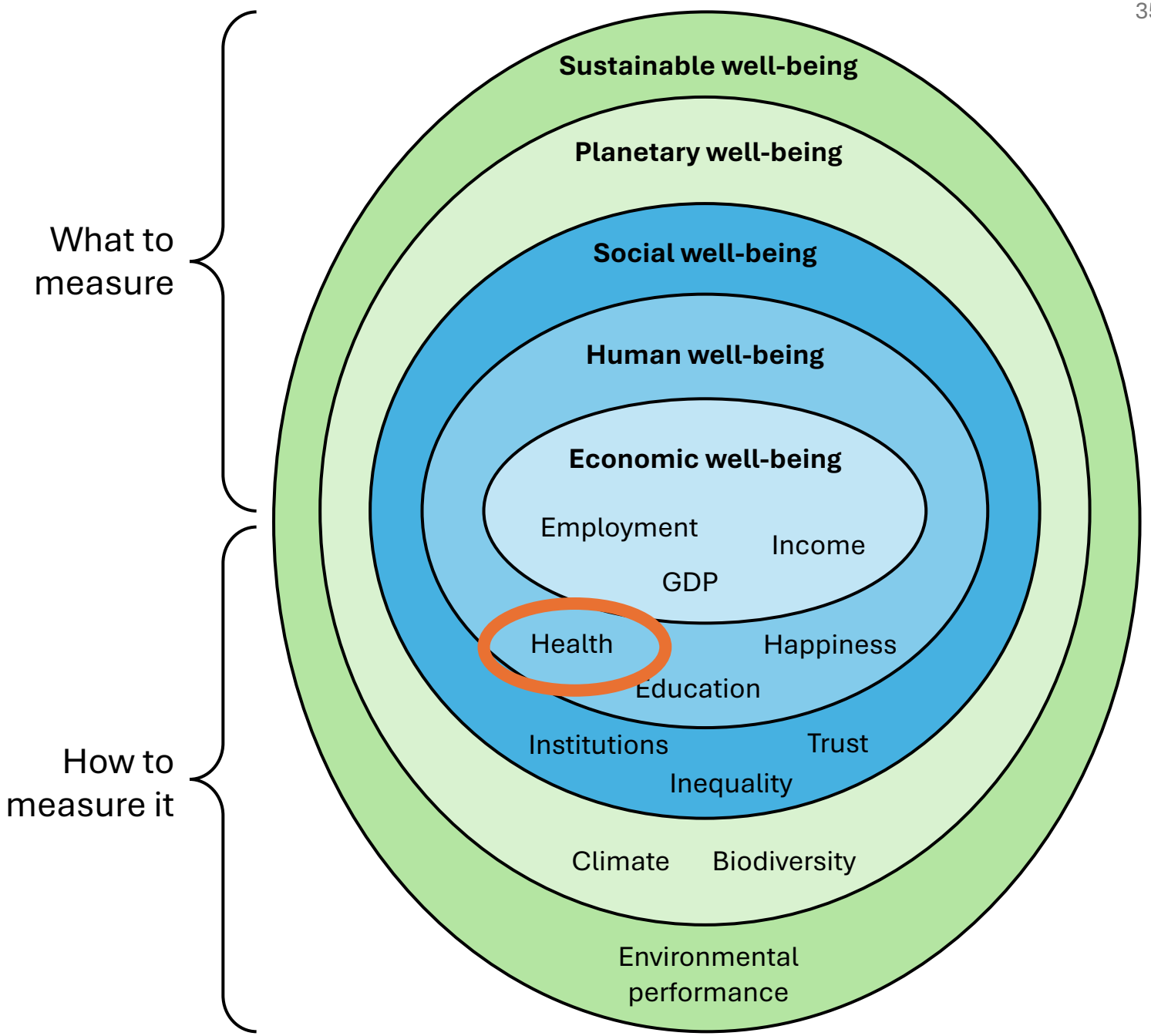


Other composite indicators to explore

- Better life index
  - Allows user to assign their own weights to different sub-indices

Health

- Beyond economic well-being
- How to measure health as an aspect of human well-being



Health

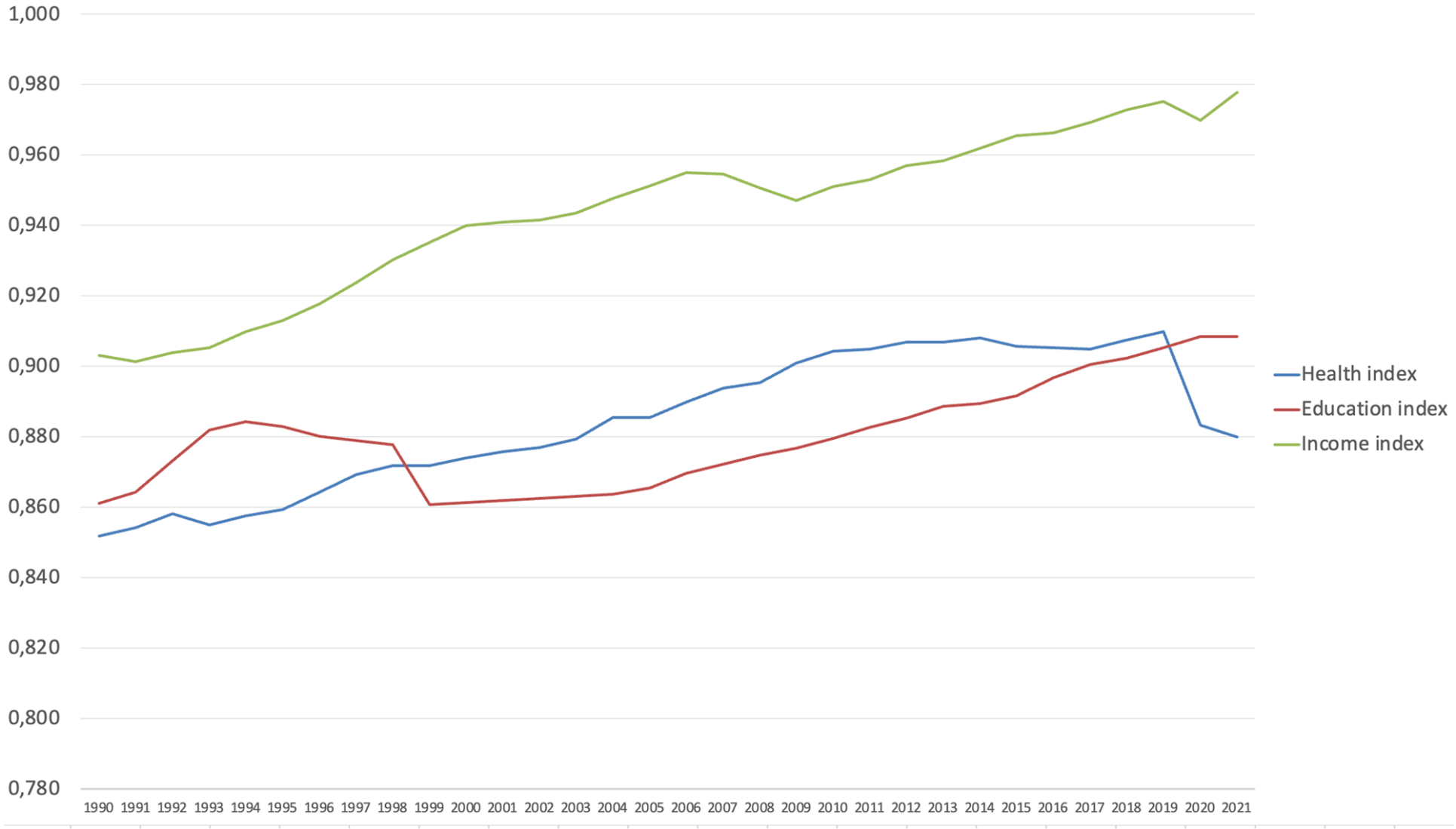
- HDI approach: life expectancy
  - Group A = Western Europe, U.S., Canada, Australia, New Zealand, and Japan
  - Group B = Africa, Asia, Eastern Europe and Latin America

Table 1–5b. **Average Life Expectation for Groups A and B, 1000–1999**
(years at birth; average for both sexes)

	1000	*1820*	*1900*	*1950*	*1999*
Group A	24	36	46	66	78
Group B	24	24	26	44	64
World	24	26	31	49	66

Source : Angus Maddison, 2001/2006.

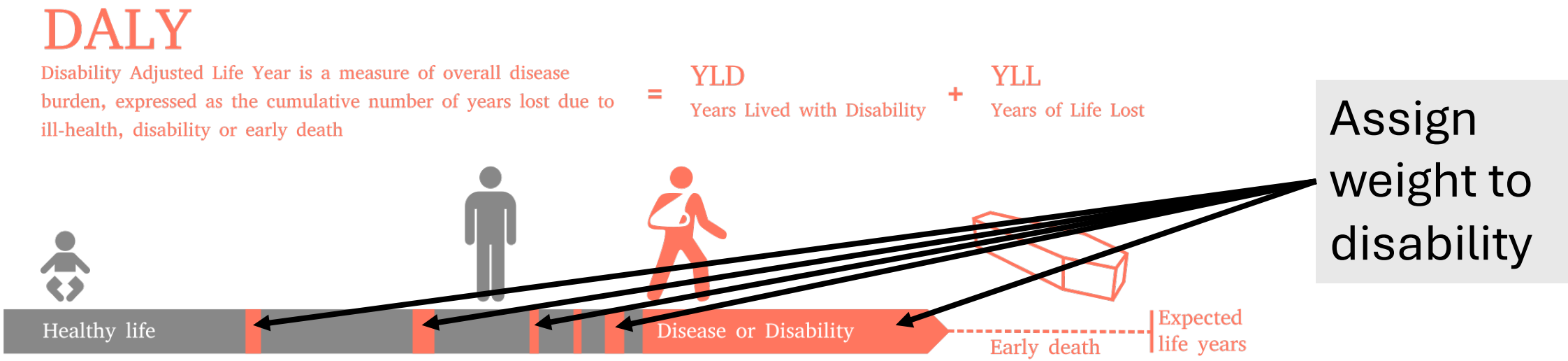
Health: HDI and the case of the U.S.



Tønnessen, M. Wasted GDP in the USA. *Humanit Soc Sci Commun* **10**, 681 (2023). https://doi.org/10.1057/s41599-023-02210-y

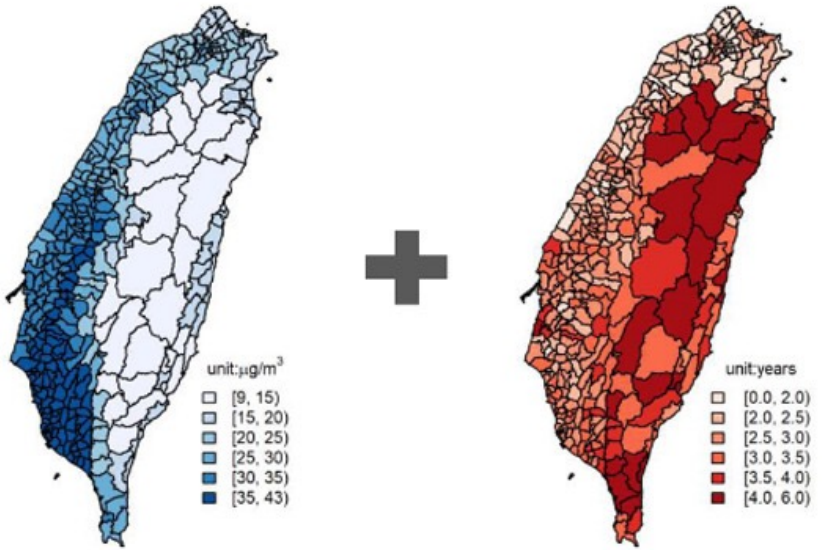
Health: Measuring Quality

- World Health Organization: Disability-Adjusted Life Year (DALY)
  - Loss of the **equivalent of one year of full health**
  - DALYs for a disease or health condition are the **sum** of the **years of life lost to due to premature mortality (YLLs)** and the **years lived with a disability (YLDs)**



Health and the built environment: The importance of indoor and outdoor air pollution

Study population: Study cohorts of 3.5 million older adults aged ≥65 years living in 350 townships in Taiwan were constructed.



Lifetime mean $PM_{2.5}$ exposure

Lifetime expected DALYs

Standard stepwise regression analysis

Main Findings

lifetime mean exposure to $PM_{2.5}$

Every 10-μg/m³ increase

DALYs due to cardiopulmonary disease

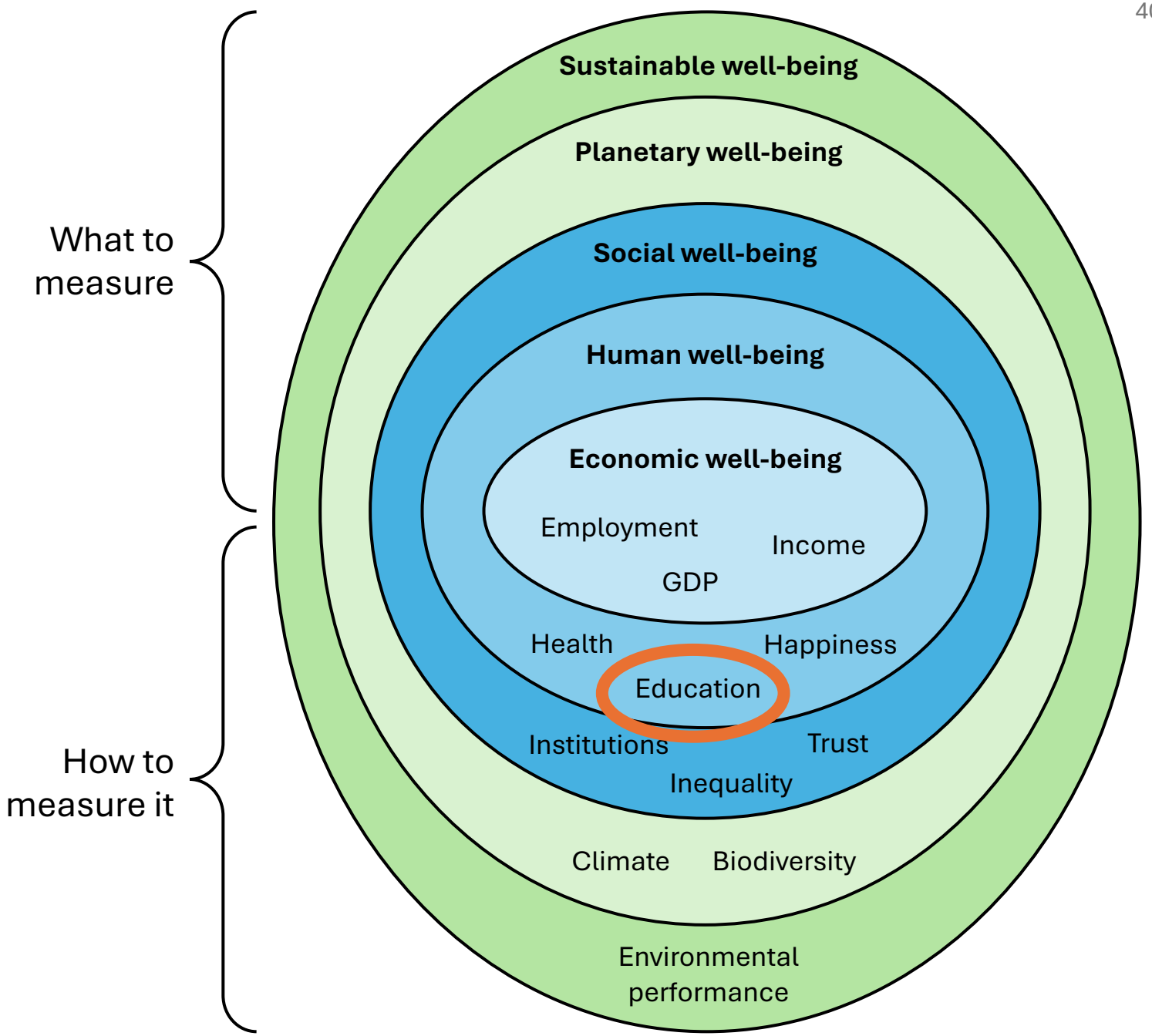
0.25 years of health losses individually

Conclusion: Our study suggests that significant health co-benefits could be gained and health inequalities could be mitigated by reducing ambient air pollution levels.

https://doi.org/10.1016/j.scitotenv.2022.158901

Education

- Education is another aspect of human well-being



Education: HDI approach

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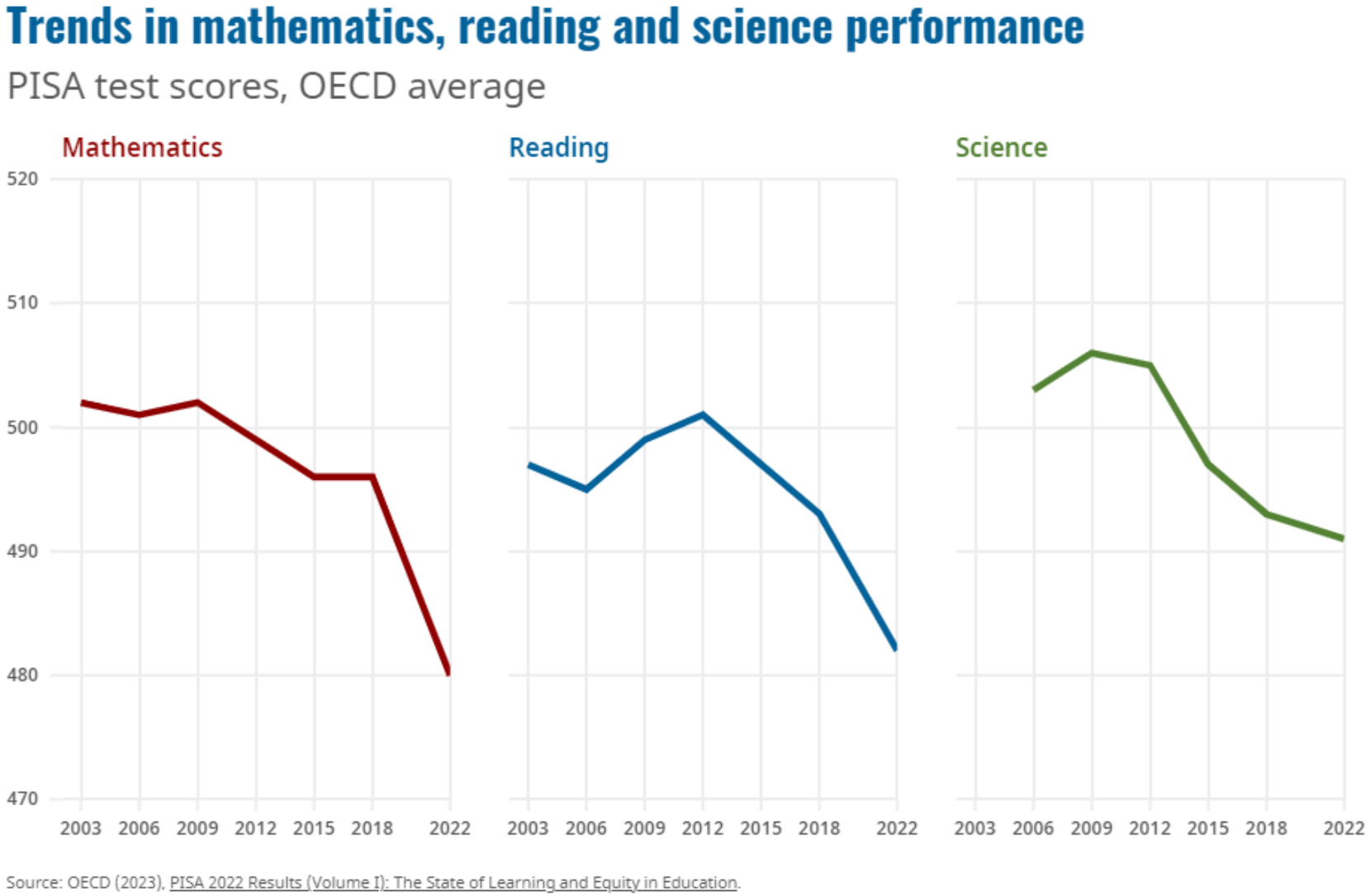
Potential education for a given country

Actual education achieved in a given country on average

Education: Beyond HDI

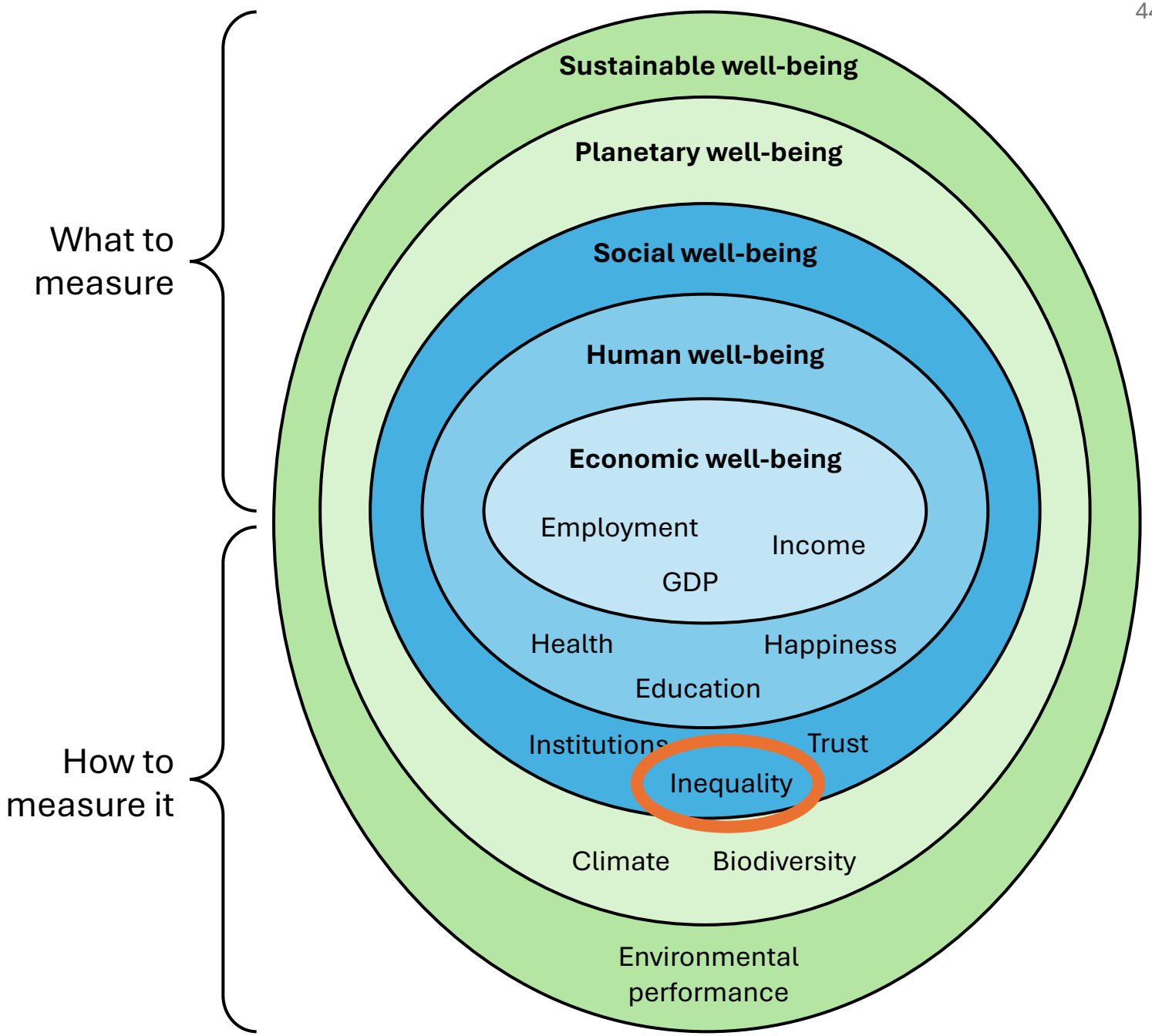
- Important to measured effectiveness of education beyond years of schooling
- Need to teach people how to learn
- The OECD Program for International Student Assessment (PISA) examines “not just what students know in mathematics, reading and science, **but what they can do with what they know**”
  - Paper based tests give in OECD countries to students between the ages of 15 years 3 months and 16 years 2 months

PISA results



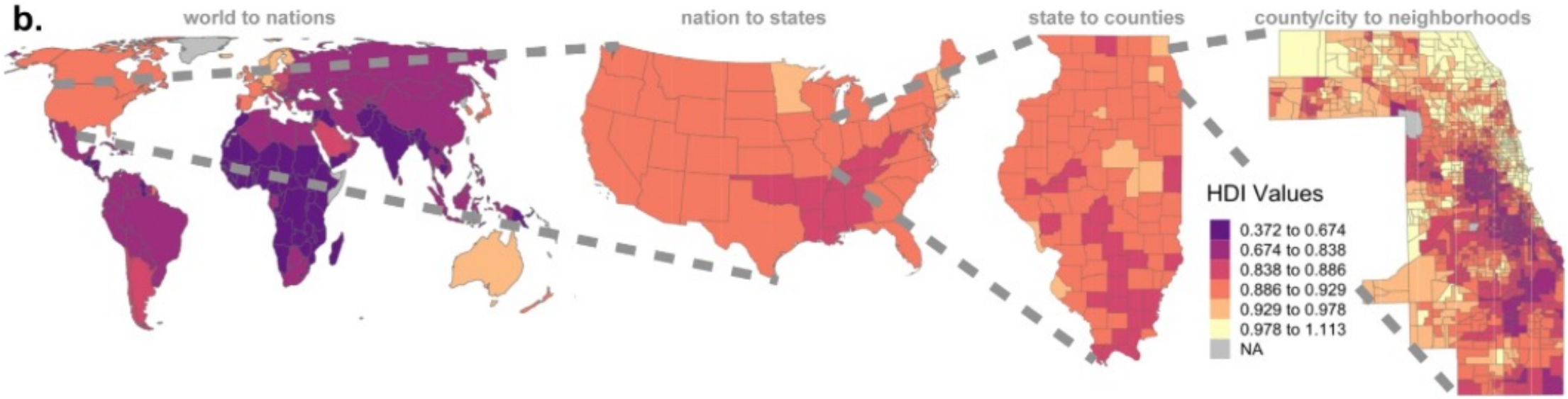
Inequality

- Social well-being accounts for the fact that societies are comprised of collections of individuals



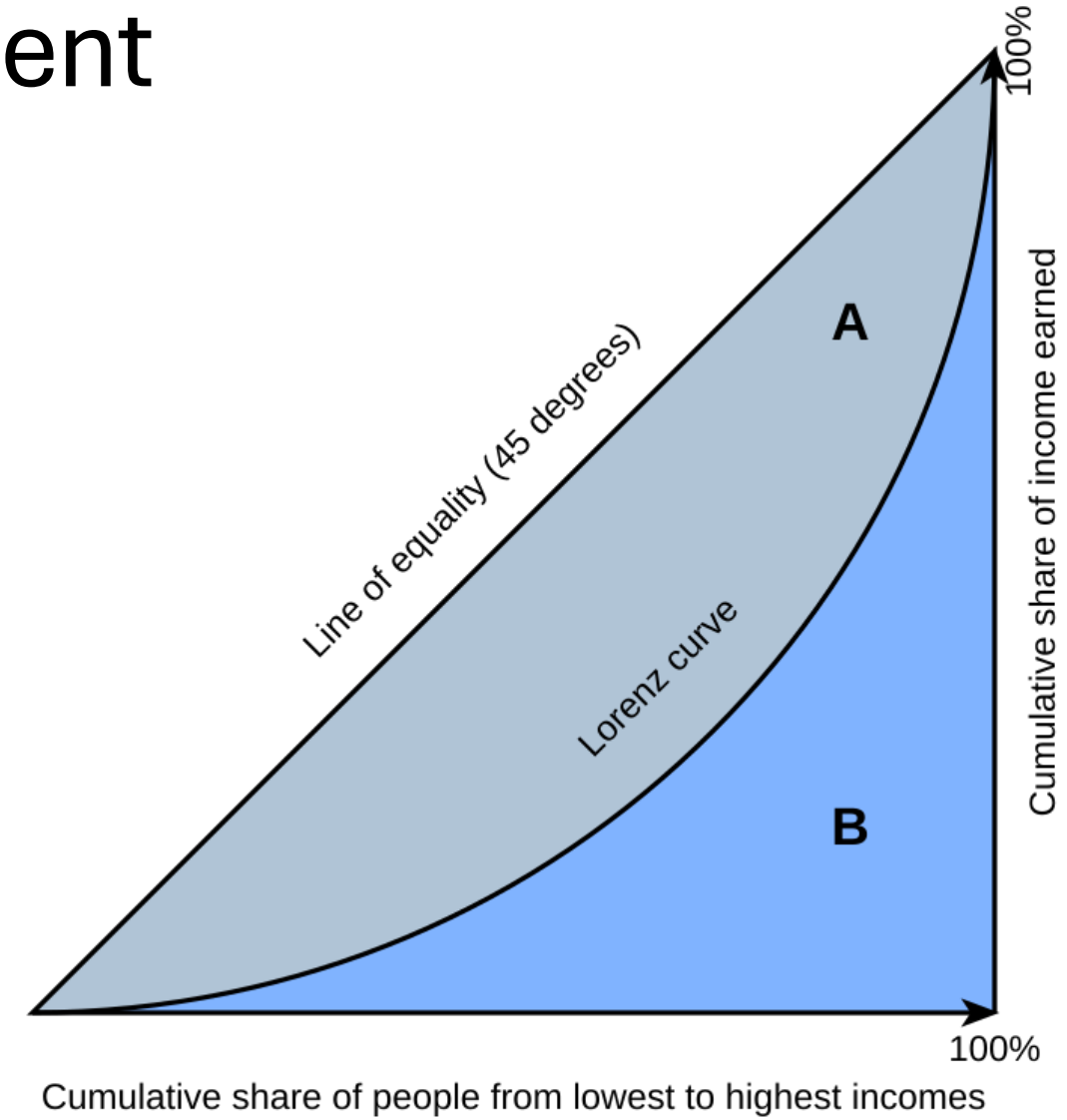
Inequality

- Many metrics we have seen so far (e.g. HDI) provide a single value for a particular place (e.g. country)
- What if we are concerned about the distribution of the index within that place?



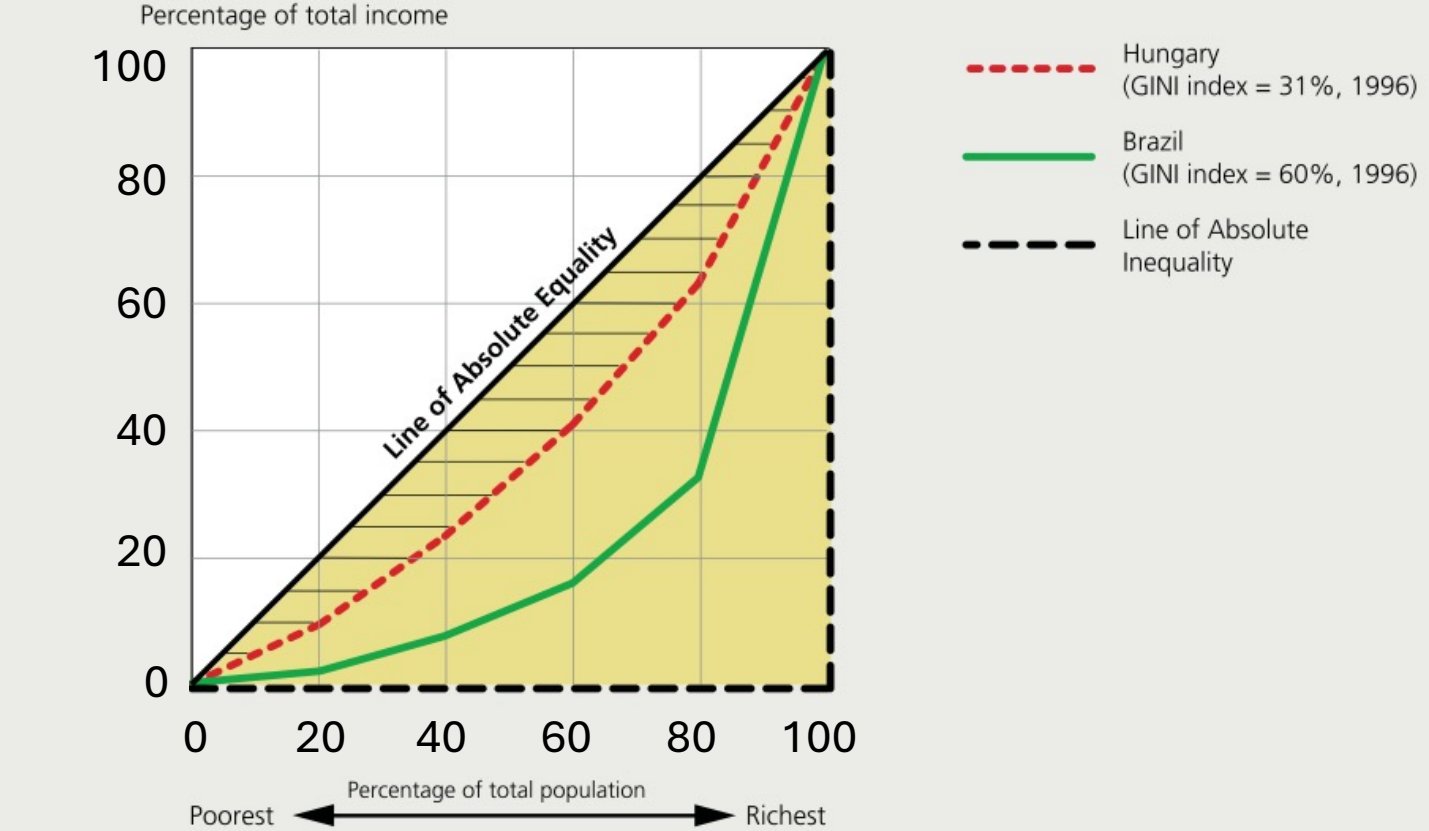
Inequality: Gini coefficient

- x-axis: arrange people from lowest to highest income
- y-axis: cumulative income (total income for given share of population)
- The Lorenz curve represents the particular area's data
- The line of equality represents each person having the same income
- Gini = A/(A+B)



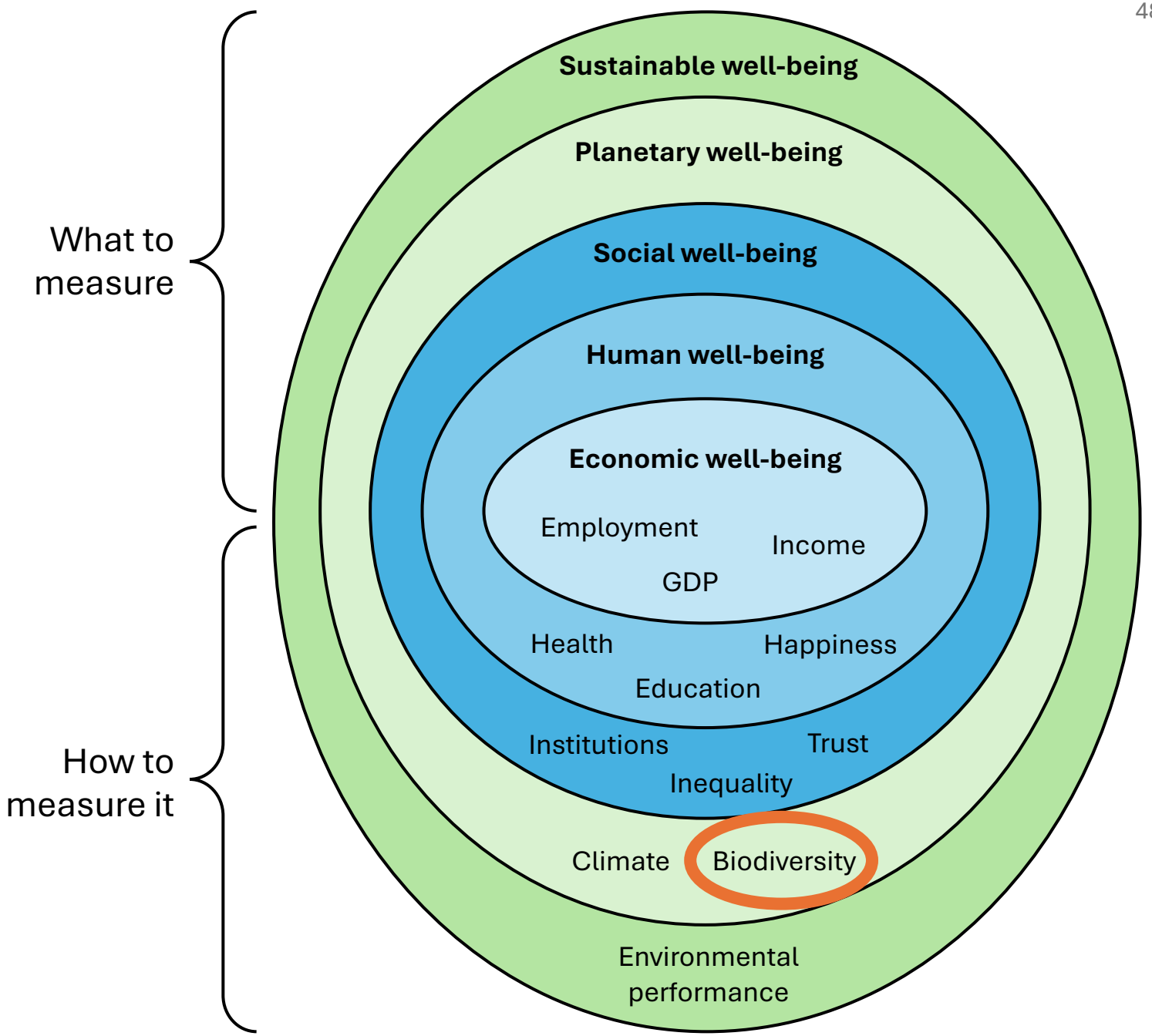
Consider the following plot of Hungary and Brazil's Lorenz curves. How much of the country's wealth belongs to the top 20% of earners in Brazil?

A. 81%
B. 34%
C. 44%
D. 66%



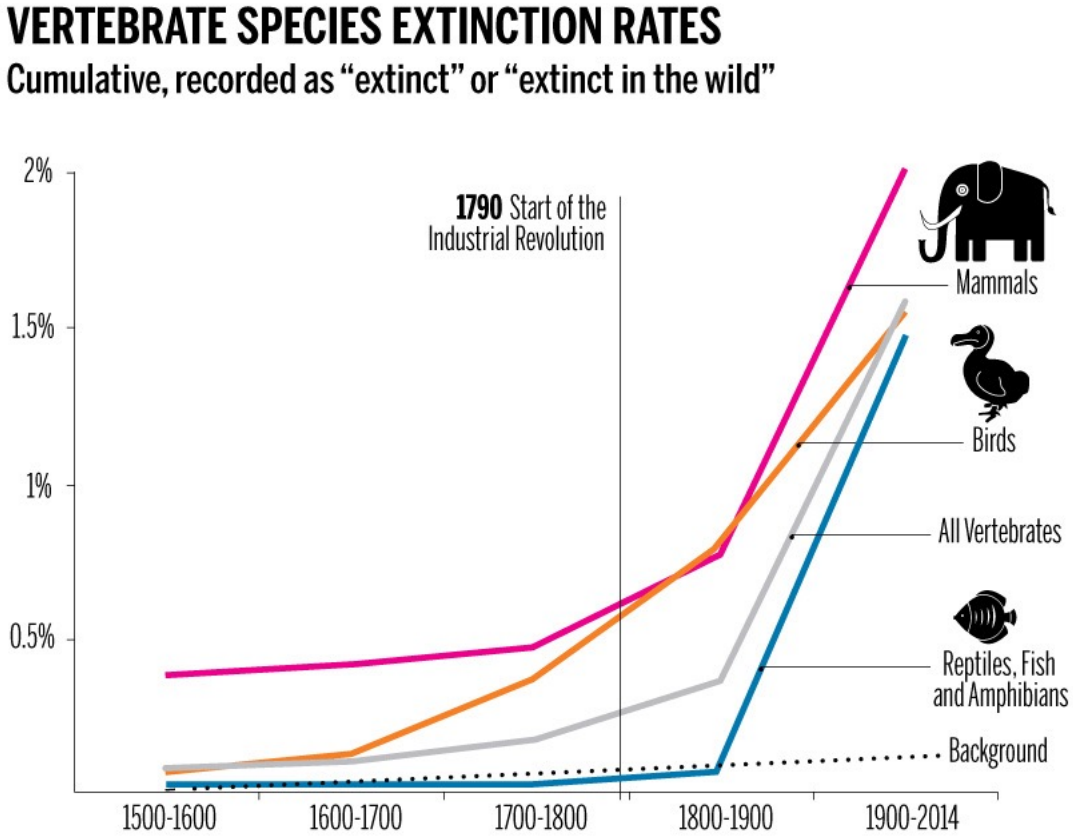
Biodiversity

- We've already talked about climate as an aspect of planetary well-being
- Biodiversity is another important component



Biodiversity

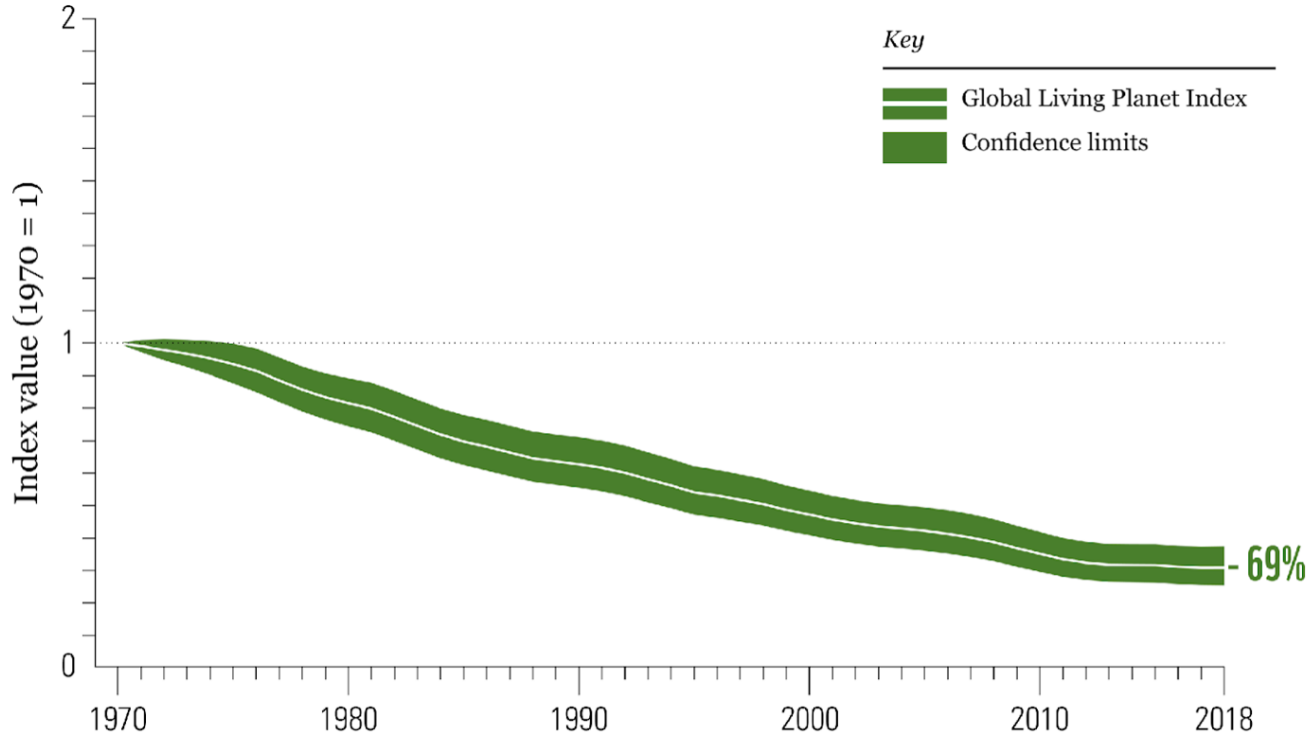
- The biosphere: all living organisms and their environments in ecosystems
  - There are several million species
  - Biodiversity is a component of the biosphere
- Biodiversity refers to a diversity of all aspects of life, including genes, species, and ecosystems
- We are currently experiencing a large acceleration in the extinction of species due to human activities



CEballos et al. Sci. Adv. 2015:1:e1400253

Measuring biodiversity

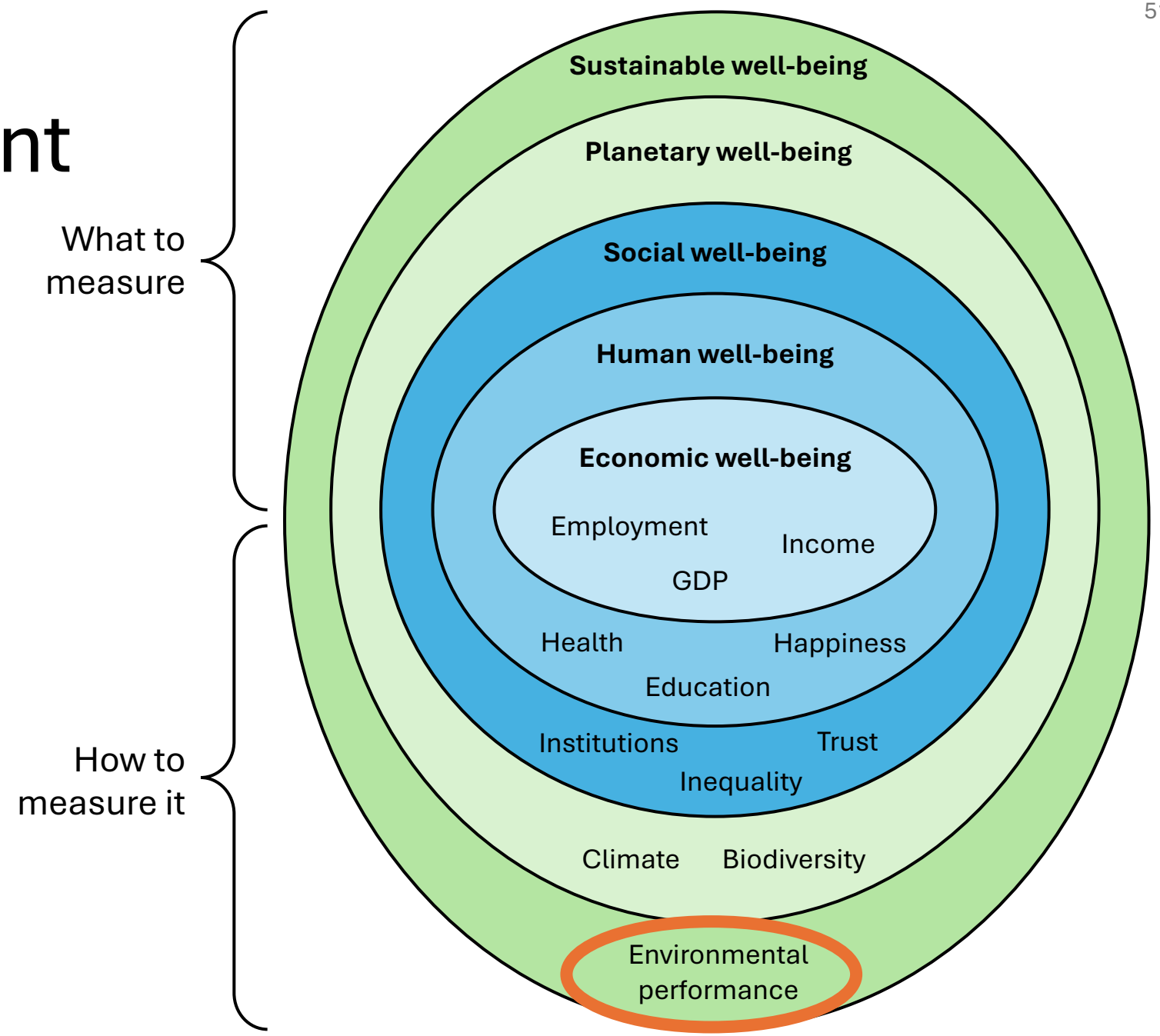
- Example: Living Planet Index
  - Based on population trends of vertebrate species around the world
- How to assign value to the health of the planet's biodiversity?
  - Will discuss in more detail later in course!



Source: Living Planet Index

Ecological footprint

- Moving toward more comprehensive indicators of sustainability…

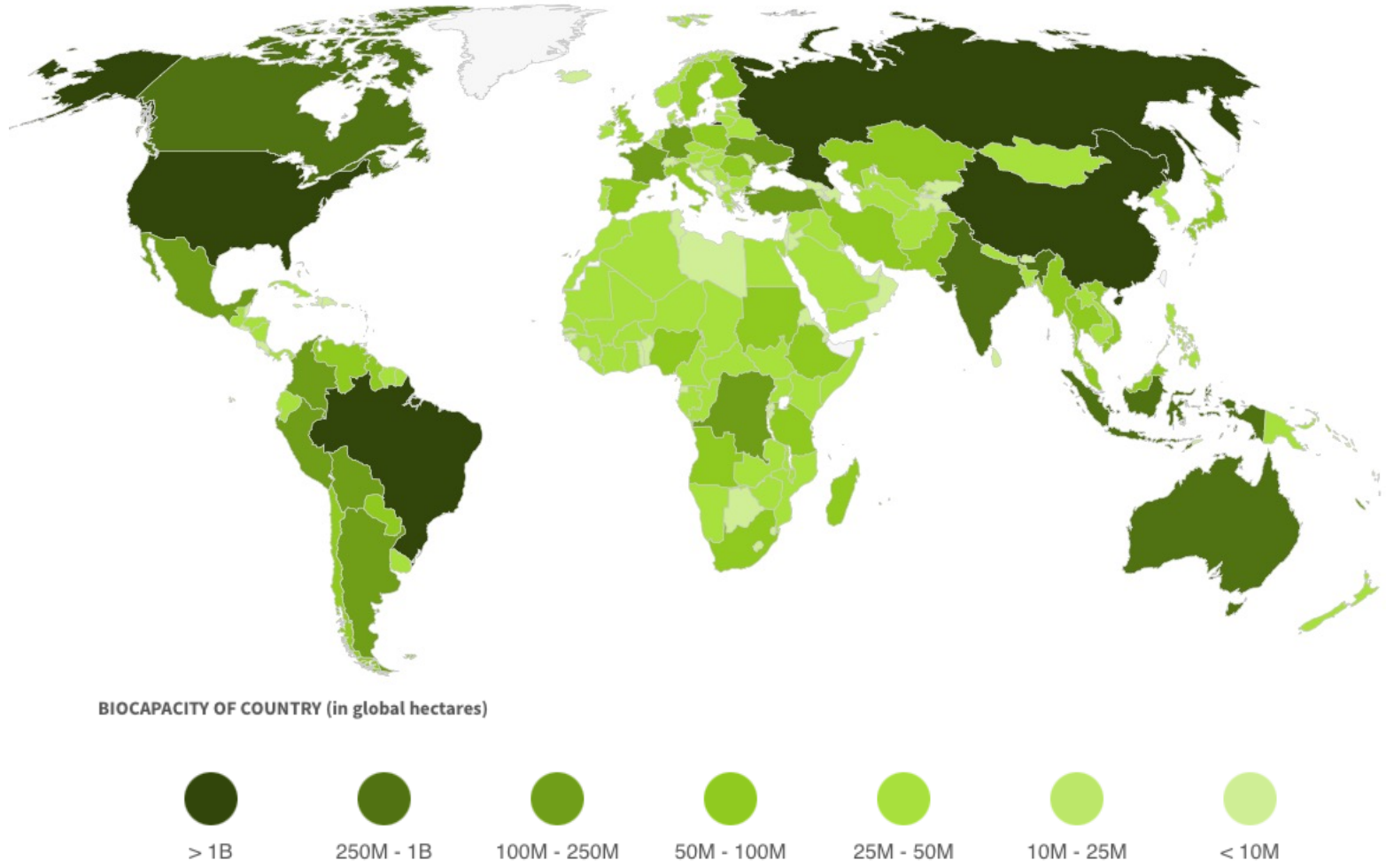


Ecological footprint

- An approach to measuring the **supply** and **demand** of nature
- The ecological footprint is a measure of:
  - the **ecological assets** required
  - by a population or product
  - to **produce the natural resources consumed**, including
    - plants
    - livestock and fish
    - timber and other forest products
    - space for cities
  - and to **absorb its waste** (especially CO2)

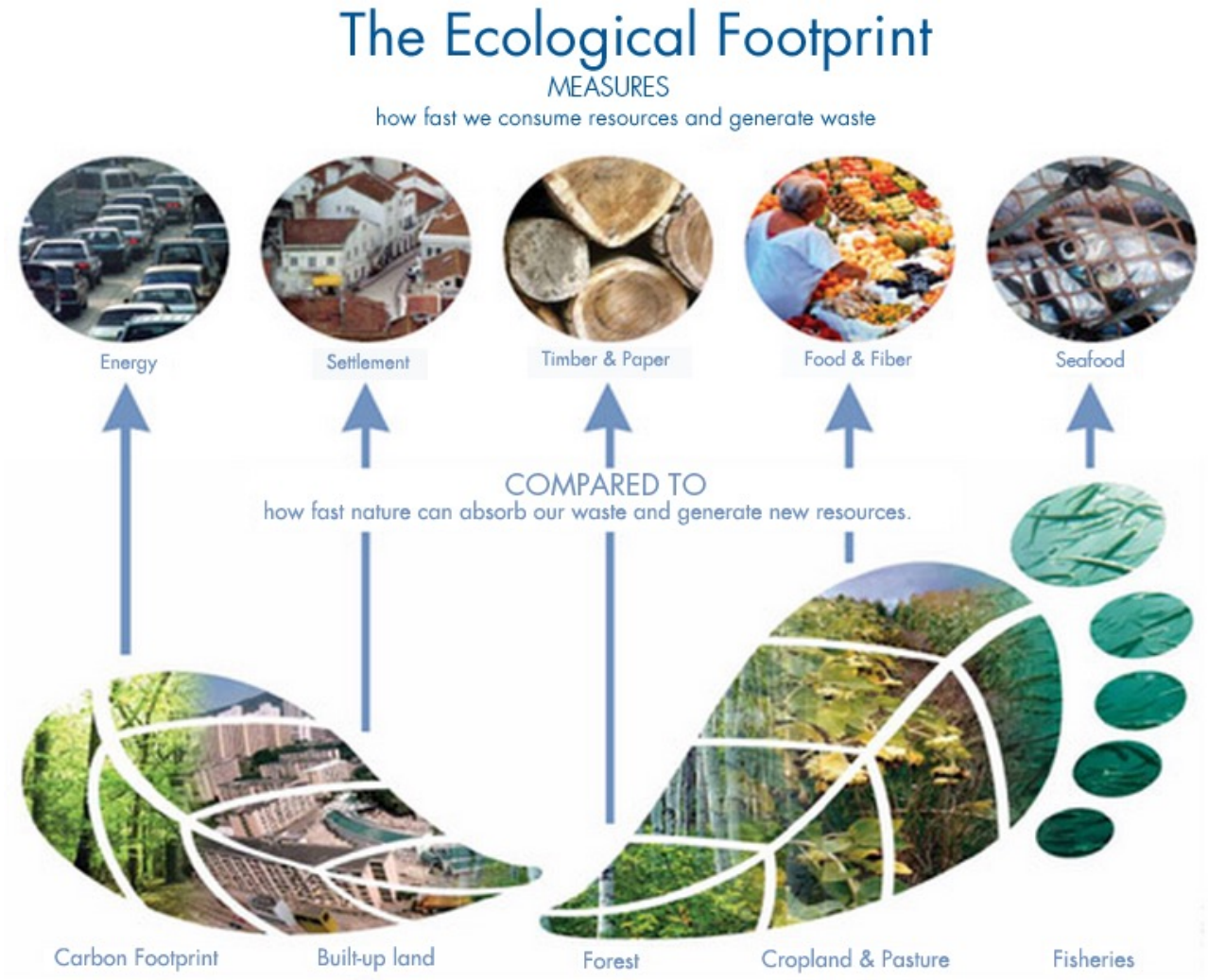
Supply: Biocapacity

- Biocapacity is the **total regenerative capacity** available to serve demands from human activities
- Measured in global hectares



Demand: Ecological footprint

- Tracks use of productive surface areas of the Earth
  - Cropland
  - Grazing land
  - Fishing grounds
  - Built-up land
  - Forest area
  - Carbon demand on land



Productive surface areas of the Earth

Footprint component definitions

CARBON UPTAKE FOOTPRINT:	Calculated as the amount of forest land required to absorb CO_2 emissions from burning fossil fuels, land-use change and chemical processes, other than the portion absorbed by oceans
GRAZING LAND FOOTPRINT:	Calculated from the area used to raise livestock for meat, dairy, hide and wool products
FOREST FOOTPRINT:	Calculated from the amount of lumber, pulp, timber products and fuel wood consumed by a country each year
FISHING GROUNDS FOOTPRINT:	Calculated from the estimated primary production required to support the fish and seafood caught, based on catch data for 1,439 different marine species and more than 268 freshwater species
CROPLAND FOOTPRINT:	Calculated from the area used to produce food and fibre for human consumption, feed for livestock, oil crops and rubber
BUILT-UP-LAND FOOTPRINT:	Calculated from the area of land covered by human infrastructure, including transportation, housing, industrial structures, and reservoirs for hydropower

Source: World Wildlife Foundation

Unit: **global hectare**

- Hectare: 10,000 square meters
- Unit for measuring both ecological footprint (demand) and biocapacity (supply)
- A global hectare is a unit representing a **biologically productive hectare** with **world average productivity**
- Can be thought of as a standardized spatial unit

$$1\ \text{gha} = \frac{\text{Global annual amount of biological production for human use and waste absorption}}{\text{Total hectares of biologically productive land and fisheries}}$$

Source: Footprint network

Global hectare

- General equation:

$$GH\ [gha] = Y \cdot EF\ \left[\frac{gha}{ha}\right] \cdot A\ [ha]$$

- EF = equivalence factor: translates a specific land type (e.g., cropland, forest land) into a global hectare
- Y = yield factor: general adjustment not accounted for in EF
  - **For biocapacity (supply):** Y = country-specific yield factor of biocapacity of a specific land type
  - **For ecological footprint (demand):** Y = global yield factor by type of consumption → translates a product into area [ha] to produce that product

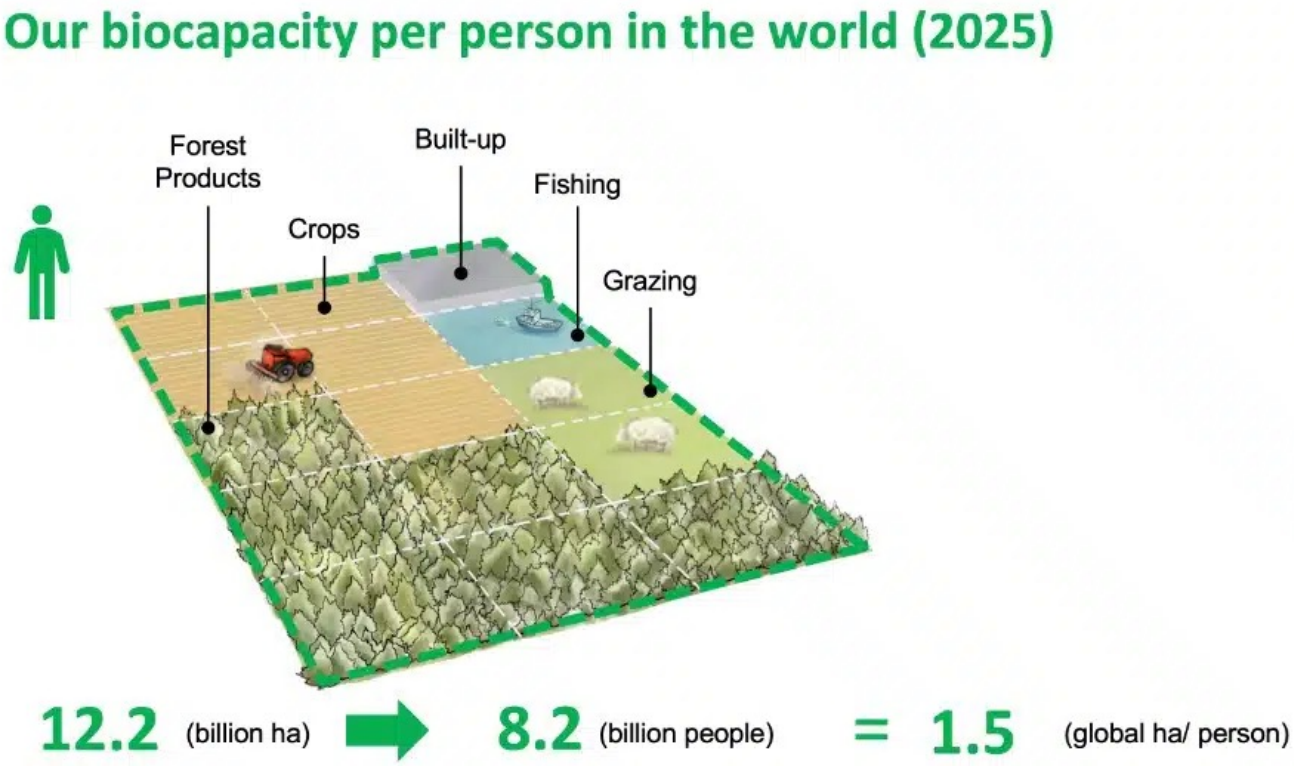
T 2 Equivalence factors in 2002

Energy	Fertile cropland (vegetable products)	Less-fertile cropland (vegetable products)	Pastureland (animal products)	Fisheries	Forest	Built-up area
1.38	2.19	1.80	0.48	0.36	1.38	2.19

Source: Swiss Federal Offices

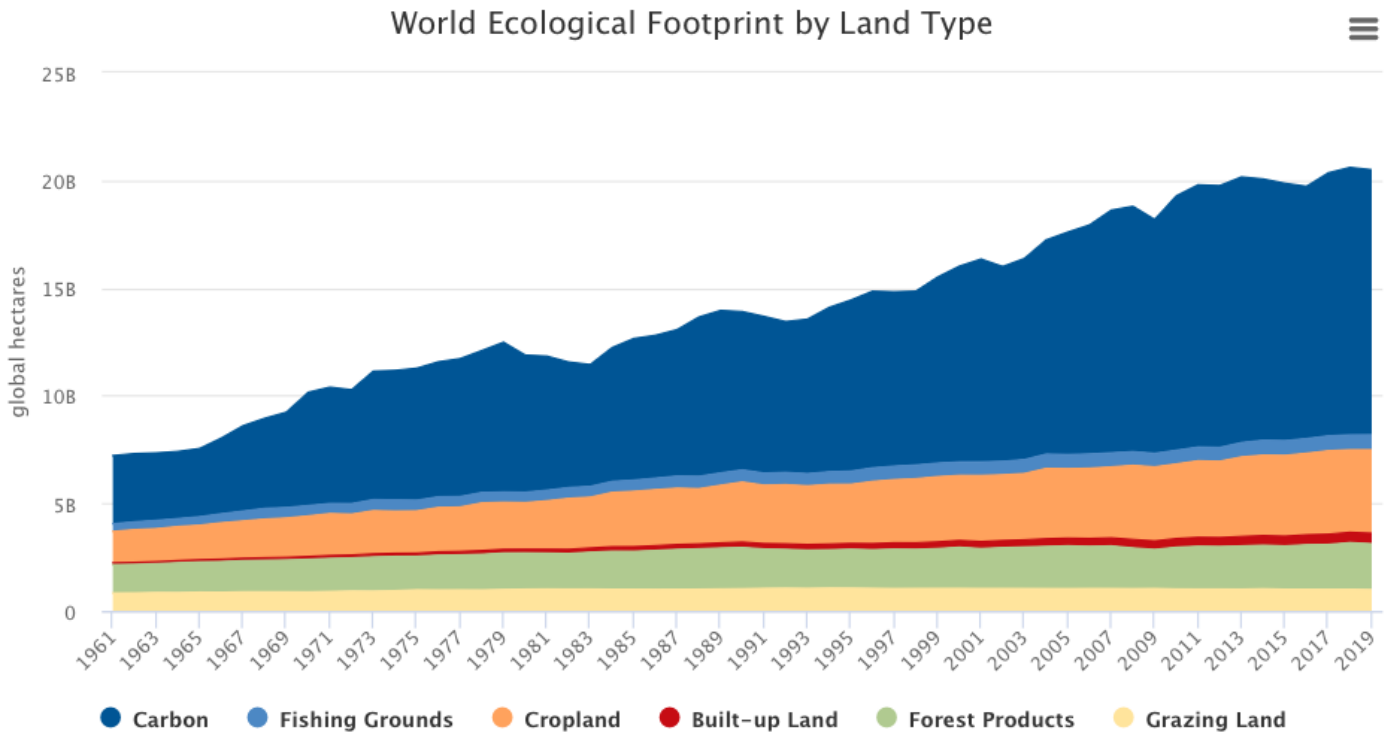
Global hectares of supply

- Biocapacity is the total number of global hectares of biologically productive land

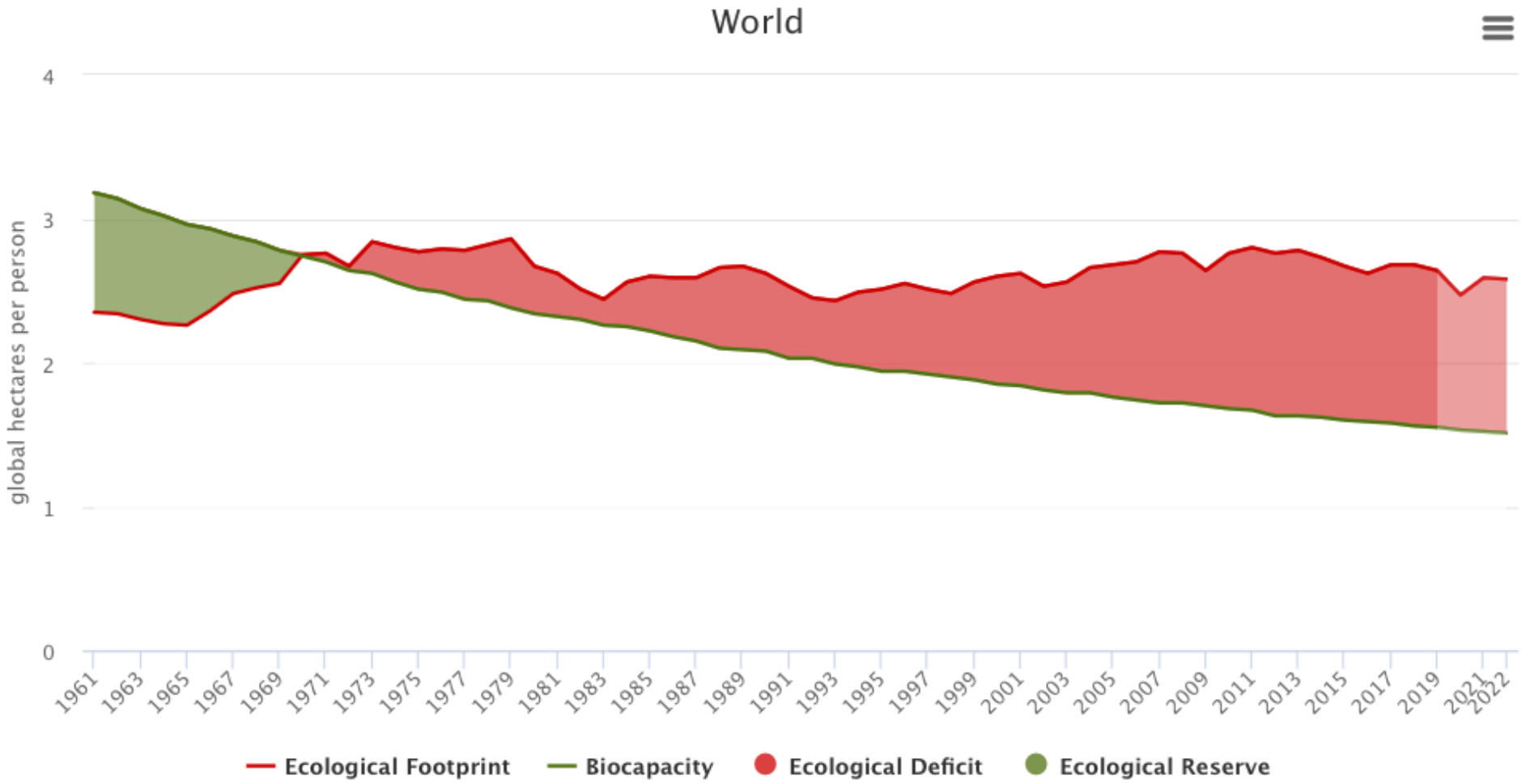


Global hectares of demand

- Ecological footprint is measured in global hectares for different types of demand on the Earth
- How do we account for spatial boundaries? Consumption vs. production? Recall Lecture 1 on territorial carbon emissions and consumption carbon emissions



Supply vs. Demand



Source: Footprint network