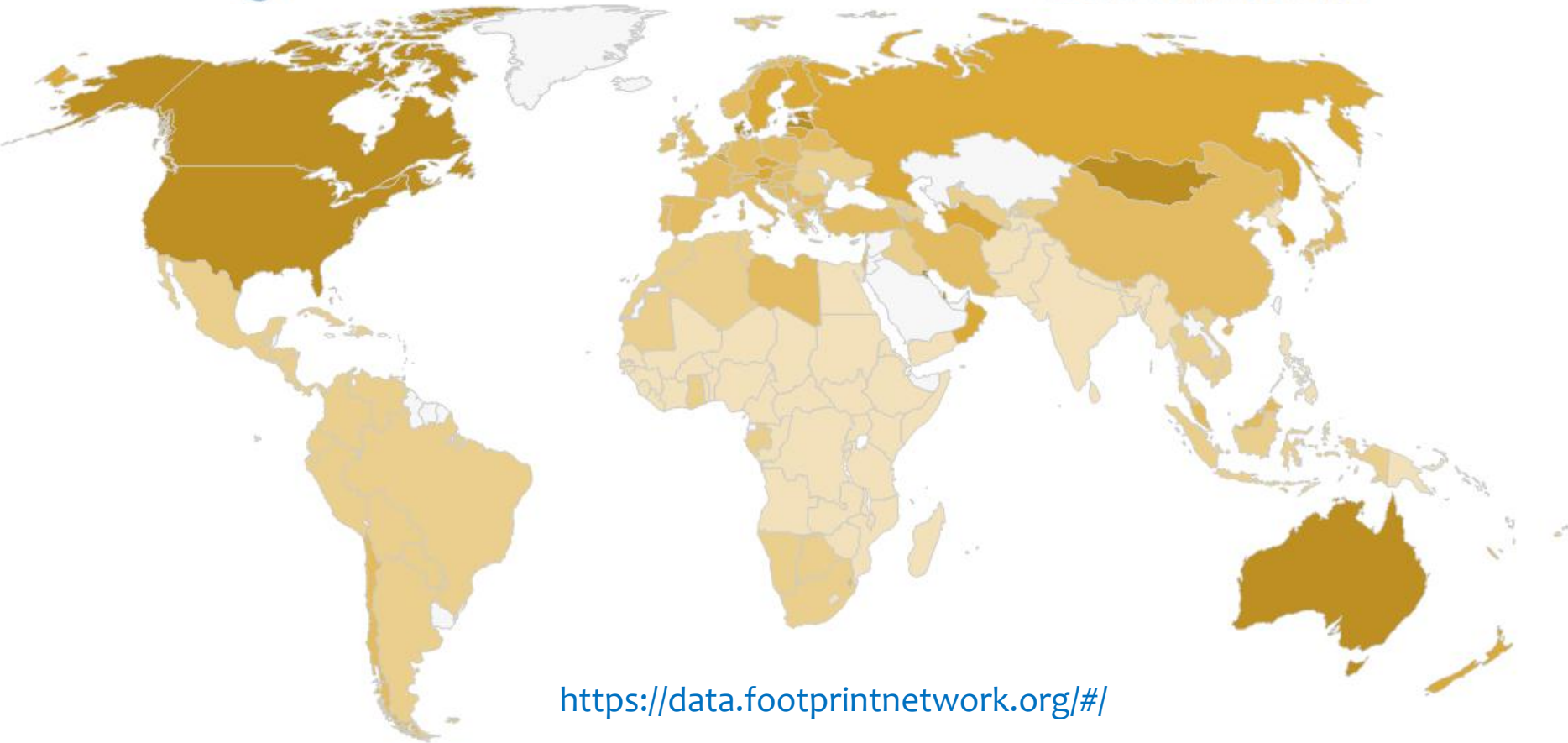


# **Sustainability and Chemistry**

## **CH5106: L5**

Instructors: Sayam Sengupta  
Swaminathan Sivaram  
Amitava Das




<https://data.footprintnetwork.org/#/>


**ECOLOGICAL FOOTPRINT PER PERSON:** THE Nation's total Ecological Footprint divided by the total population of the nation. The available biocapacity per person on our planet is currently 1.6 global hectares.

**ECOLOGICAL FOOTPRINT PER PERSON OF COUNTRY'S POPULATION (in global hectares)**

  
>6.7

  
5.1-6.7

  
3.4-5.1

  
1.7-5.1

  
<1.7

X

## WORLD (2024) (ESTIMATE)

GDP PER PERSON

\$13,428

POPULATION

8,118,839,808

Biocapacity  
per person

1.5

gha

Ecological Footprint  
per person

2.6

gha

BIOCAPACITY  
RESERVE(+)/DEFICIT(-)

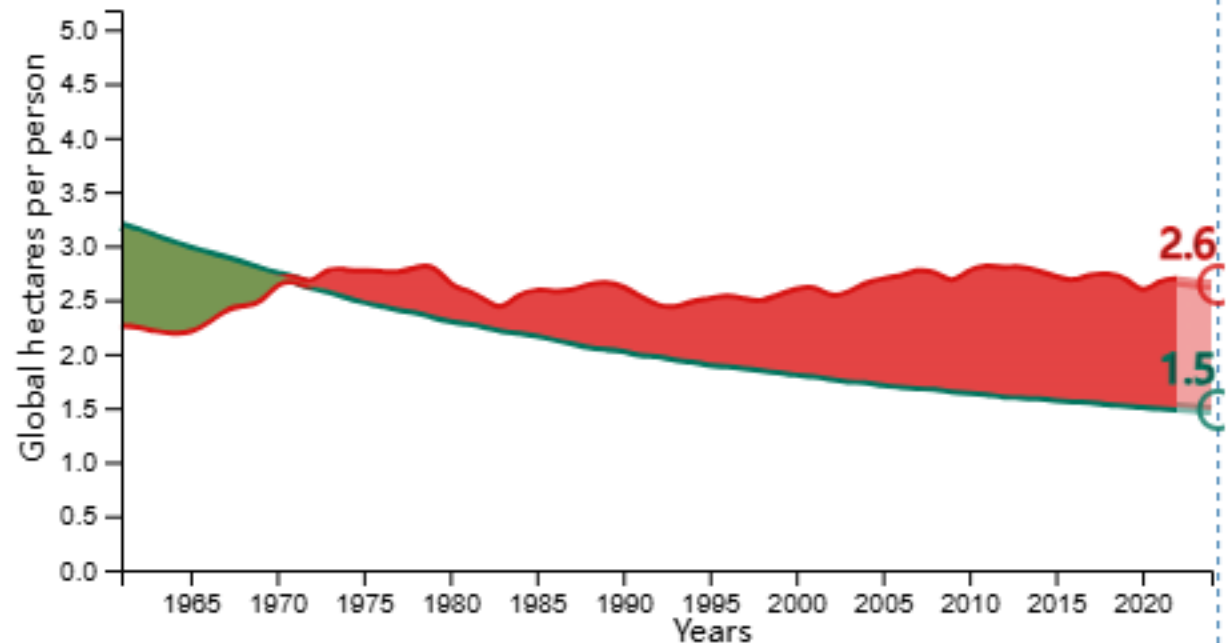
-1.1

gha

Ecological Footprint and  
Biocapacity  
From 1961 to 2024  
(last 2 years are estimates)

Ecological  
Footprint per  
person

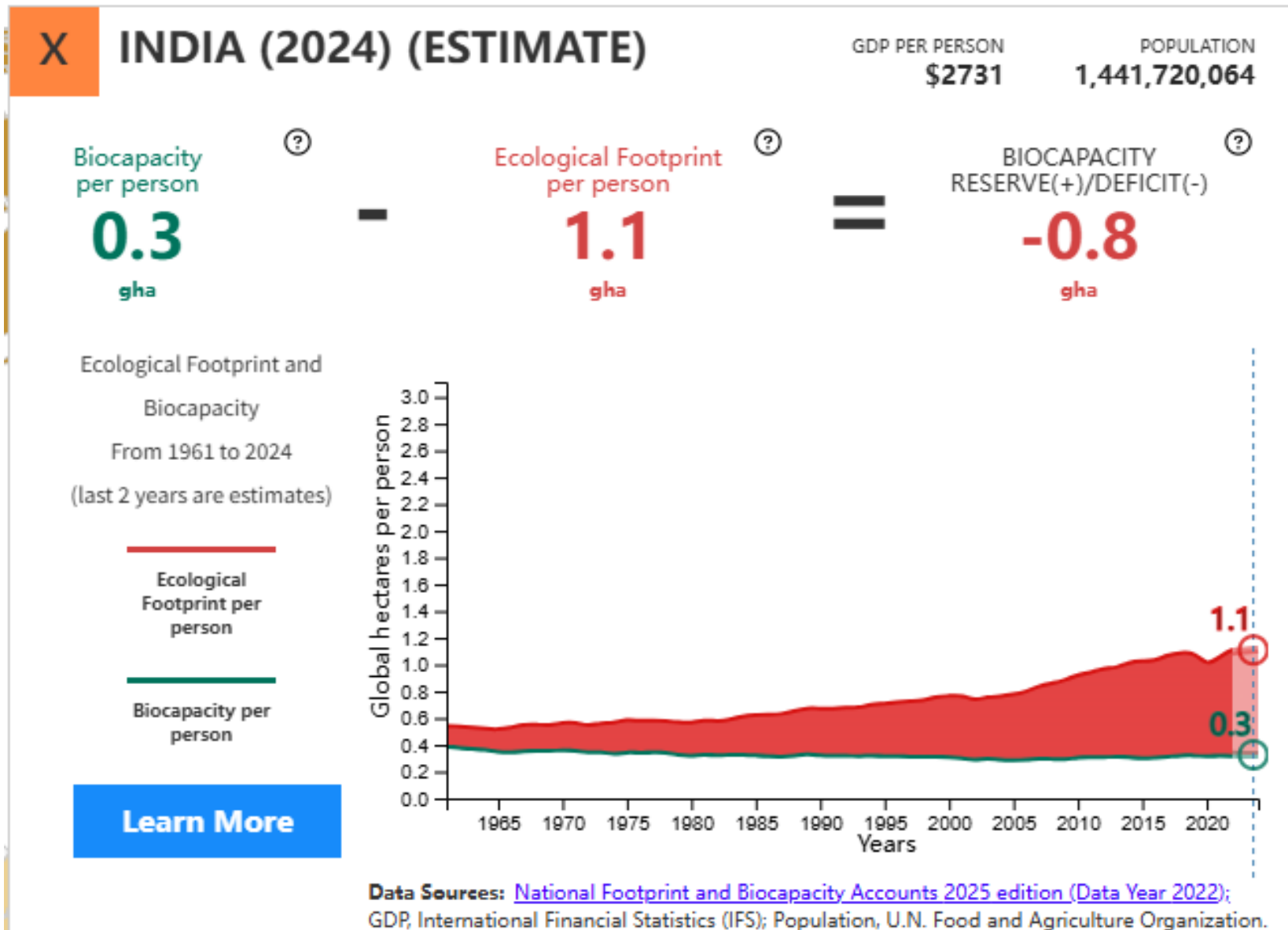
Biocapacity per  
person

[Learn More](#)

**Data Sources:** [National Footprint and Biocapacity Accounts 2025 edition \(Data Year 2022\)](#);  
GDP, International Financial Statistics (IFS); Population, U.N. Food and Agriculture Organization.

Humanity's Ecological Footprint and the planet's biocapacity in global hectares per person from 1961 to 2022 (2023 edition). [data.footprintnetwork.org](https://data.footprintnetwork.org)

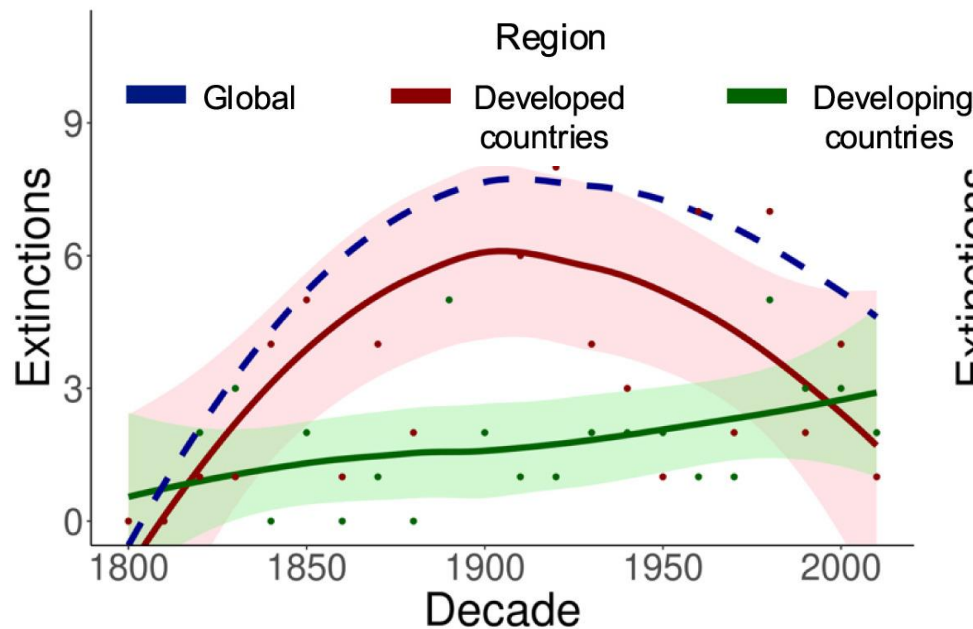
Ecological deficit / reserve OR biocapacity deficit / reserve: The difference between the biocapacity and Ecological Footprint of a region or country. An ecological deficit occurs when the Footprint of a population exceeds the biocapacity of the area available to that population. Conversely, an ecological reserve exists when the biocapacity of a region exceeds its population's Footprint.



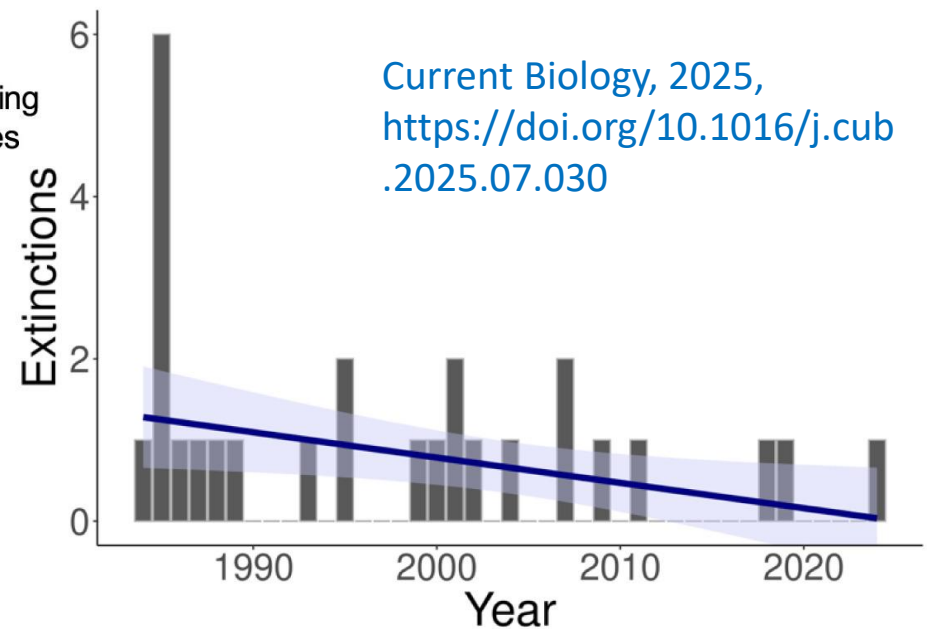
Many economically developed countries are shifting an increasing proportion of their environmental impacts to other countries by importing goods, while developing countries are accelerating their domestic land-use change to produce goods for export.

Birds: The best-studied class of animals for qualitative prediction

They show that trade-driven shifts in land use can accelerate extinction rates, particularly in developing regions, and may trigger a future global resurgence of extinctions.



The rate of avian extinctions from land-use change



The global rate of bird extinctions caused partially or primarily by land use.

Current Biology, 2025,  
<https://doi.org/10.1016/j.cub.2025.07.030>

## Trade of economically and physically scarce virtual water in the global food network

Sci Rep 11, 22806 (2021). <https://doi.org/10.1038/s41598-021-01514-w>

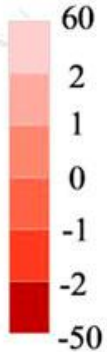
The **virtual water (VW) trade** in food refers to the volume of water used to produce crops exchanged in the global market. When assessing a country's water abundance or scarcity in the context of international virtual water trade, scholars typically consider only physical water availability, overlooking *economic water scarcity*—constraints imposed by socio-economic conditions.

A newly proposed **composite water scarcity index** (CWSI) that combines physical and economic water scarcity.

39% of virtual water volumes are exported from countries with a higher CWSI than that of the destination country. Such unfair routes occur both from low- to high-income countries and among low- and middle-income countries themselves.

The application of the CWSI reveals a shift in status—from net exporter to net importer—for some wealthy countries, and vice versa for certain low- and middle-income countries. It enables quantification of the extent to which virtual water (VW) exchanges follow environmentally and economically inequitable routes, thereby informing the development of fair compensation policies.

Classification  
Unit: Million

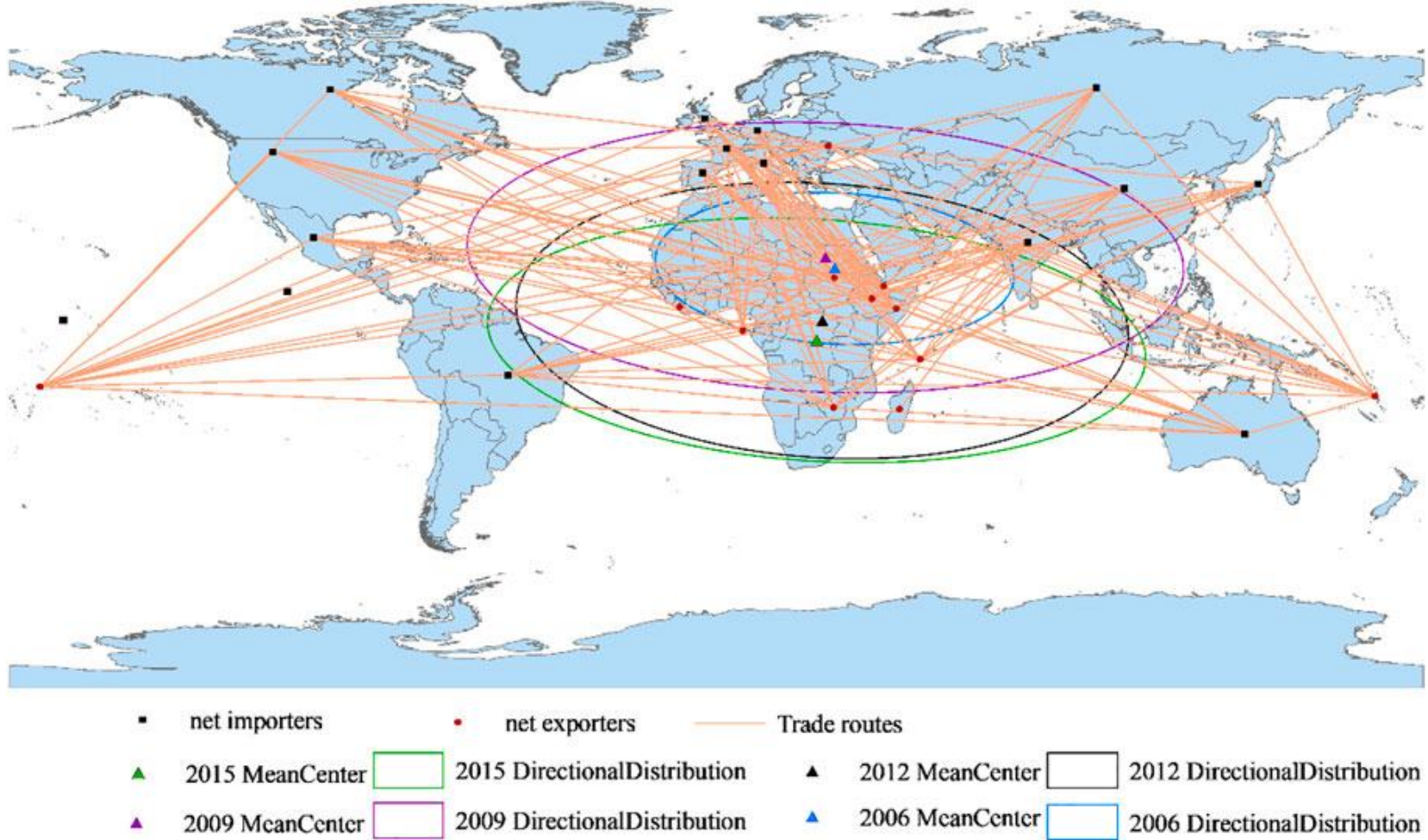


Global biodiversity footprint: The value is calculated based on the average of the net import and export footprints of biodiversity in each country.

## International Trade and Biodiversity Loss:

International trade has become a significant contributor to biodiversity loss. Understanding biodiversity impacts embedded in global supply chains is key to effective conservation. Using a [multi-regional input–output \(MRIO\)](#) model and [International Union for Conservation of Nature \(IUCN\)](#) Red List data, researchers can quantify and compare the biodiversity footprints of 188 countries/regions, highlighting how consumption in one area can threaten species in another.

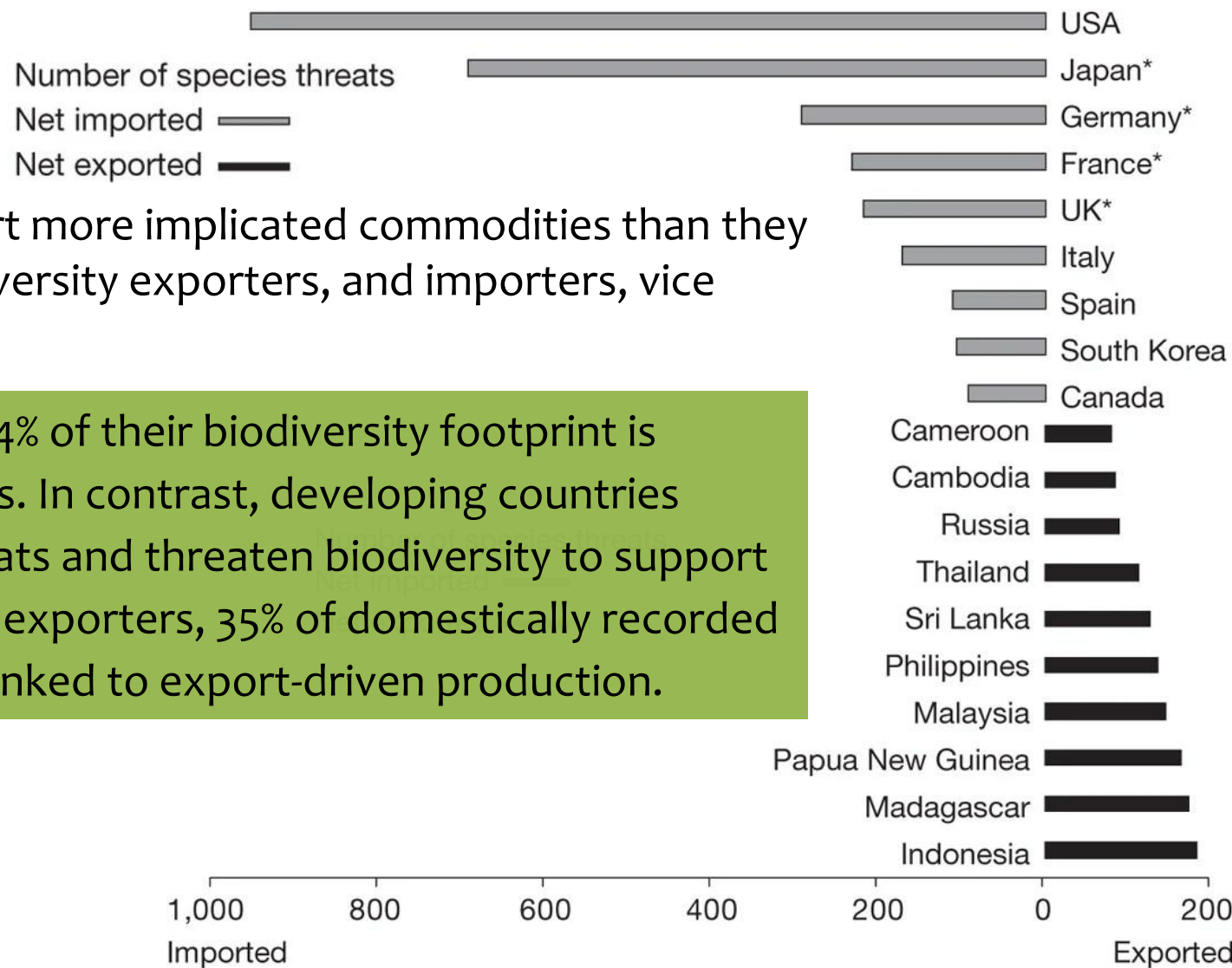
[Front. Environ. Sci. 10:1000970. doi: 10.3389/fenvs.2022.1000970](#)



Typical trade routes between countries, starting with net biodiversity importers and ending with net biodiversity exporters, reflecting the impact of the demand of final consumer countries on the biodiversity of other countries in the trade process.

**Most net importers of biodiversity: Developed or economically powerful developing countries. Net exporters: Mostly economically backward developing countries**

Agricultural trade accelerates biodiversity loss in tropical regions more than previously thought. Over 90 per cent of species loss from land use is export-driven.

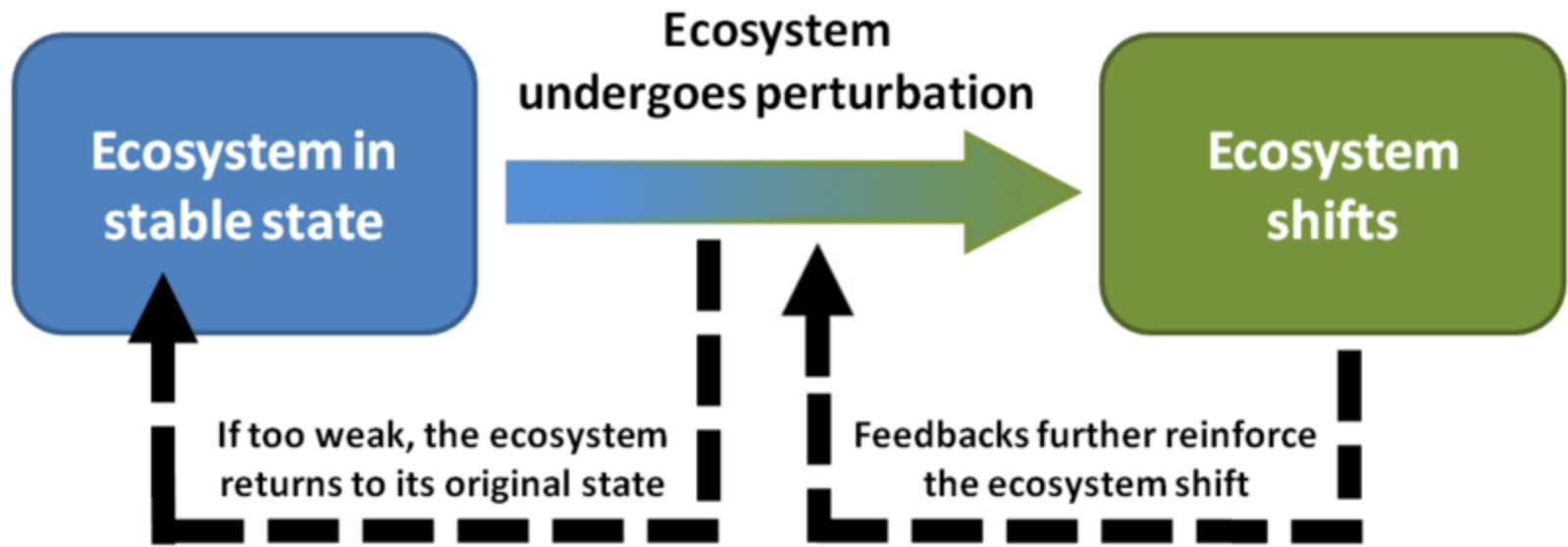


Countries that export more implicated commodities than they import are net biodiversity exporters, and importers, vice versa.

For net importers, 44% of their biodiversity footprint is attributed to imports. In contrast, developing countries often degrade habitats and threaten biodiversity to support exports. Among net exporters, 35% of domestically recorded species threats are linked to export-driven production.

“Socialism collapsed because it did not allow prices to tell the **economic truth**. Capitalism may collapse because it does not allow prices to tell the **ecological truth**”.

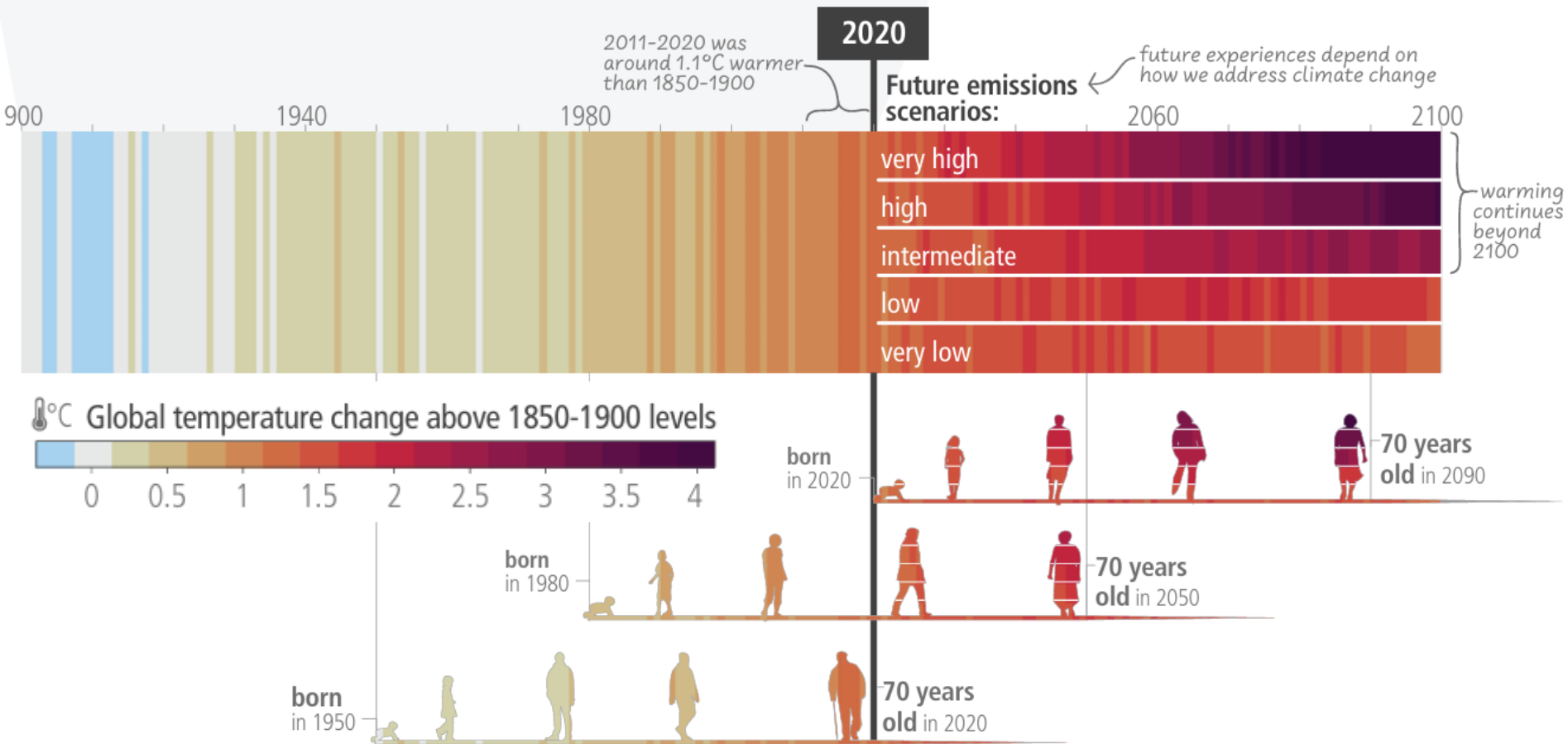
By Lester Russel Brown (born March 28, 1934);  
Environmental Analyst



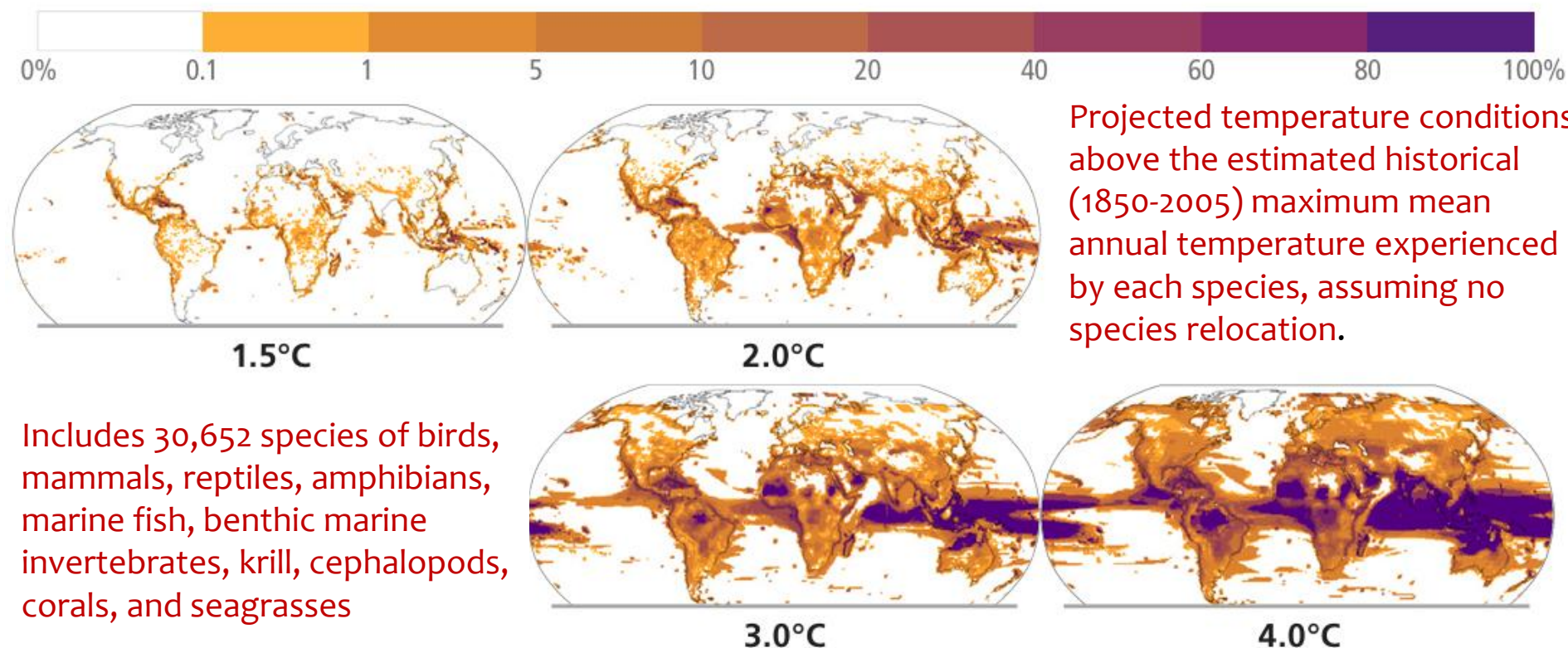
Ecosystems typically exist in stable, recognizable states maintained by balanced biological, physical, and chemical interactions. While minor disturbances can be absorbed with resilience, major or prolonged disruptions may push the system past a critical threshold, triggering a shift to an alternative stable state. This new state often differs markedly in structure and function, reinforced by self-sustaining feedbacks that lock in the altered condition.

The **Intergovernmental Panel on Climate Change (IPCC)** is an intergovernmental body of the United Nations. Its job is to "provide governments at all levels with scientific information that they can use to develop climate policies".

c) **The extent to which current and future generations will experience a hotter and different world depends on choices now and in the near term**

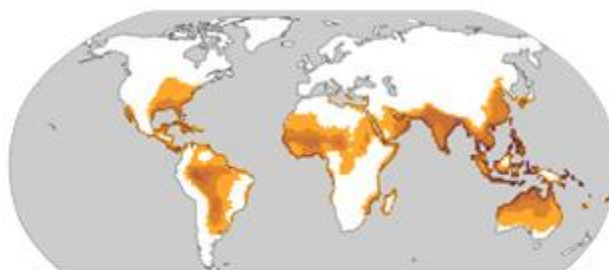


# Percentage of animal species and seagrasses exposed to potentially dangerous temperature conditions



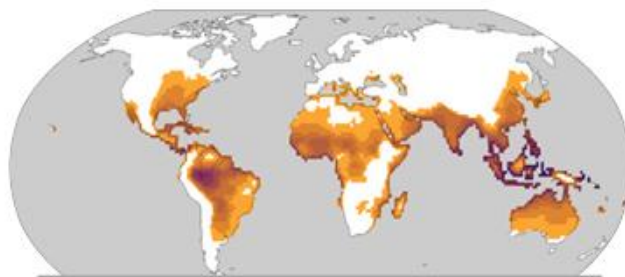


## Heat-humidity risks to human health

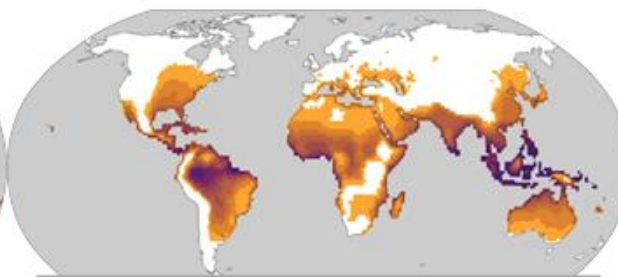


Historical 1991–2005

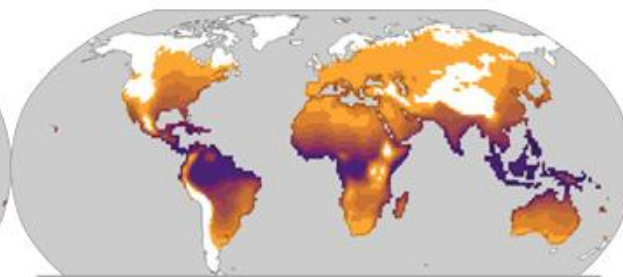
Days per year where combined temperature and humidity conditions pose a risk of mortality to individuals



1.7 – 2.3°C



2.4 – 3.1°C



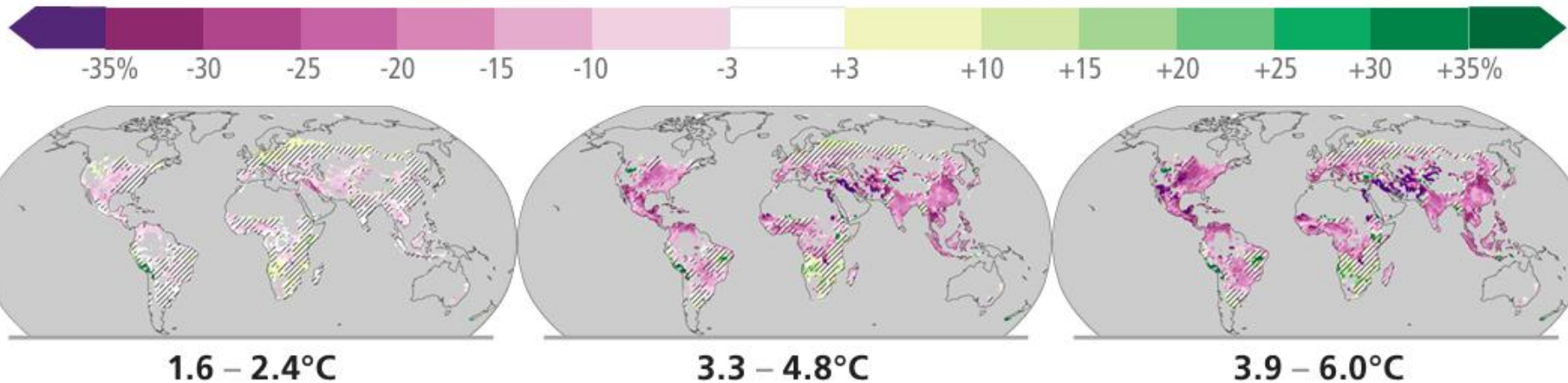
4.2 – 5.4°C

<sup>3</sup>Projected regional impacts utilize a global threshold beyond which daily mean surface air temperature and relative humidity may induce hyperthermia that poses a risk of mortality. The duration and intensity of heatwaves are not presented here. Heat-related health outcomes vary by location and are highly moderated by socio-economic, occupational and other non-climatic determinants of individual health and socio-economic vulnerability. The threshold used in these maps is based on a single study that synthesized data from 783 cases to determine the relationship between heat-humidity conditions and mortality drawn largely from observations in temperate climates.

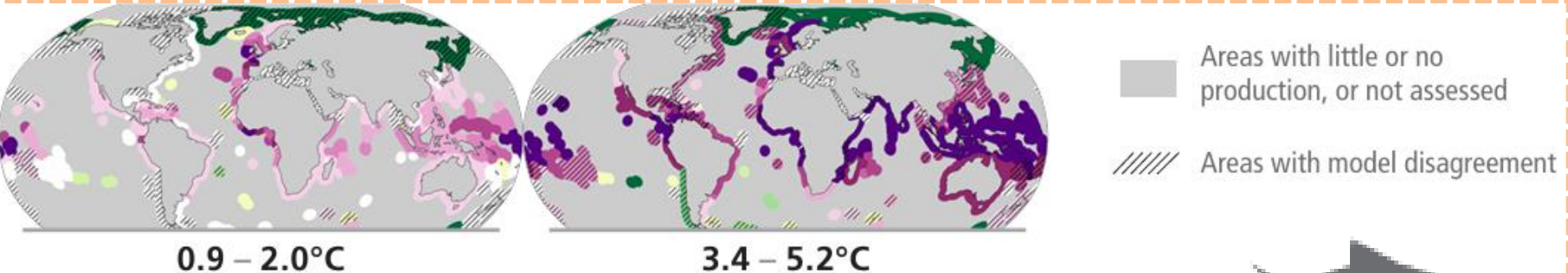
## Food production impacts



## Maize yield Changes (%)



<sup>4</sup>Projected regional impacts reflect biophysical responses to changing temperature, precipitation, solar radiation, humidity, wind, and CO<sub>2</sub> enhancement of growth and water retention in currently cultivated areas. Models assume that irrigated areas are not water-limited. Models do not represent pests, diseases, future agro-technological changes and some extreme climate responses.



## Fisheries yield (Maximum catch potential) Changes (%)

# **Namibia plans to butcher 723 wild animals including zebras, hippos, impalas, and even 83 elephants, for meat!**

ET Online: Sep 01, 2024, 09:35:00 PM IST

Deutsche Welle "German Wave", State-owned international broadcaster funded by the German federal tax budget. Thomas Latschan ; August 31, 2024

Namibia has been dealing with a drought of historic proportions. The government will now allow wild animals to be culled and their meat to be distributed to the rural population. But the move is highly controversial.

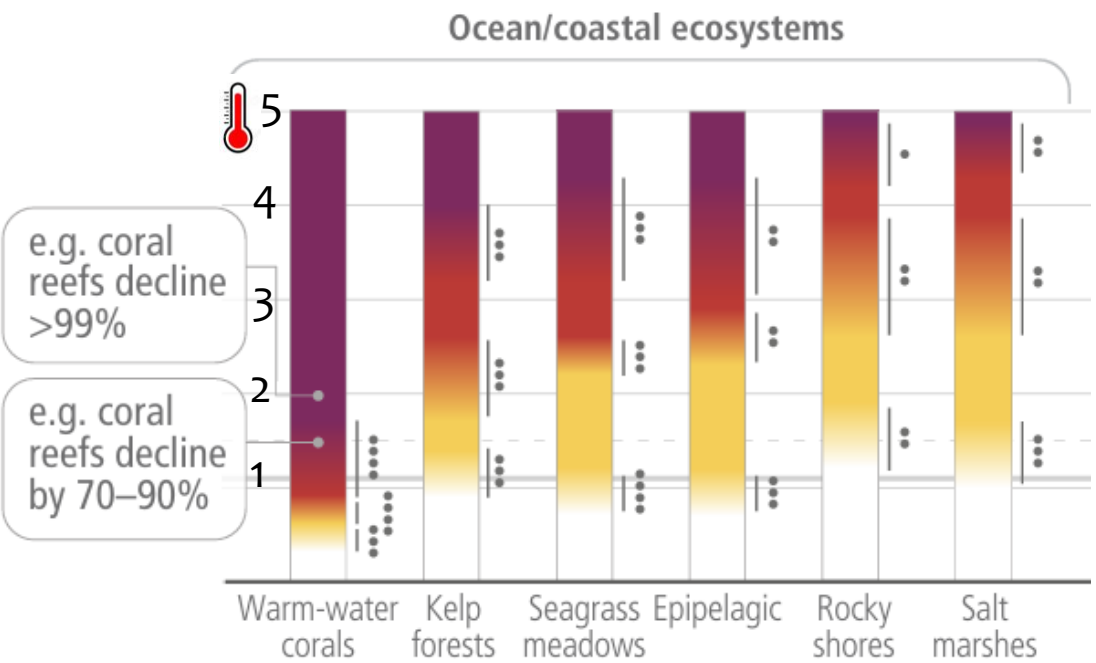
According to Namibia's Ministry of Environment, Forestry, and Tourism, the plan is "necessary" and aligns with the constitutional mandate to utilize natural resources for the benefit of Namibian citizens. The Namibian Ministry of Environment published a new statement defending the move, saying it was necessary and "in line with our constitutional mandate to use our natural resources for the benefit of Namibian citizens."

300 zebras, 30 hippos, 50 impalas, 60 buffaloes, 100 blue wildebeest, and 100 elands (a type of antelope).

The nation is also attempting to lessen interactions between humans and wildlife, which are anticipated to rise during the drought as both seek water and vegetation.

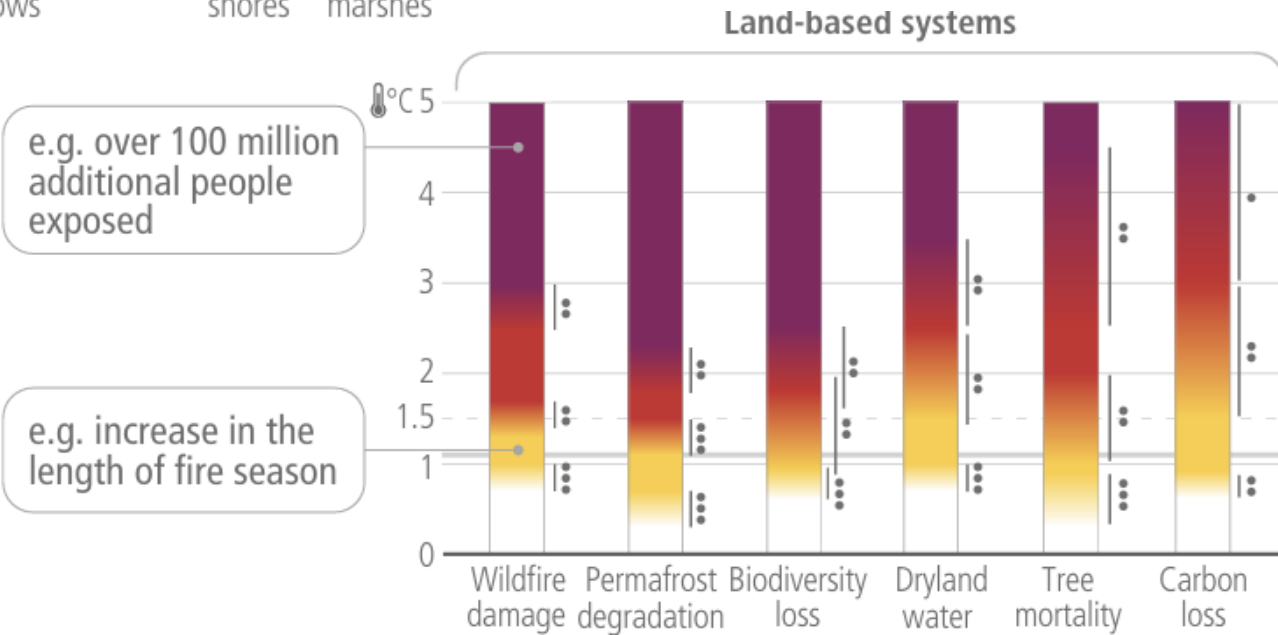
Selected global risks for land and ocean ecosystems, illustrating general increase of risk with global warming levels with low to no adaptation.

[https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC\\_AR6\\_SYR\\_SPM.pdf](https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf)



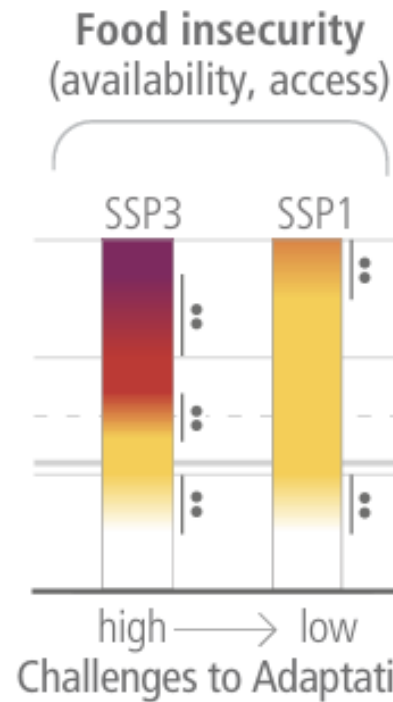
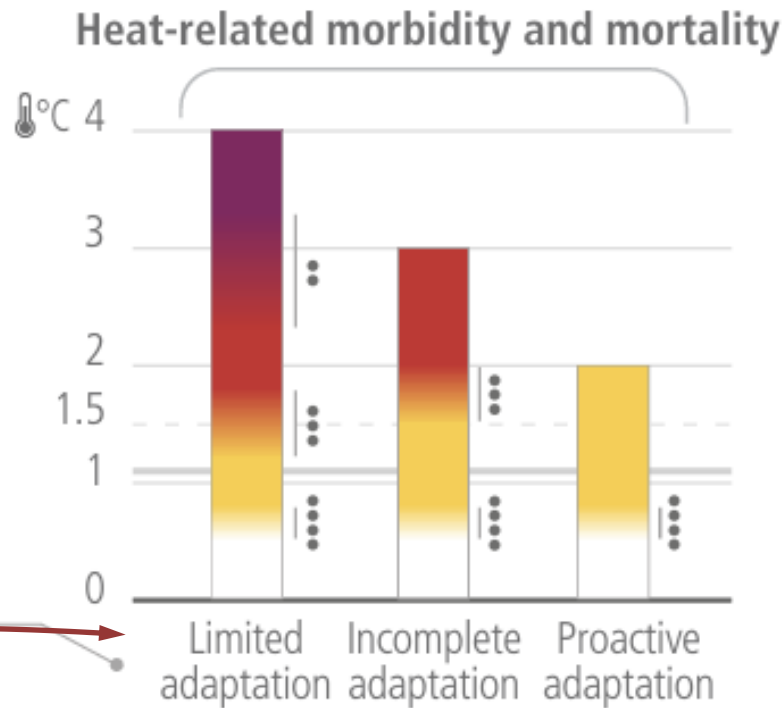
The likelihood and impacts of abrupt and/or irreversible changes in the climate system, including changes triggered when tipping points are reached, increase with further global warming (high confidence).

As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems including forests (medium confidence), coral reefs (very high confidence) and in Arctic regions (high confidence).



The diagrams are truncated at the nearest whole °C within the range of temperature change in 2100 under three SSP scenarios

Risks to food security: availability and access to food, population at risk of hunger, food price increases and increases in disability adjusted life years attributable to malnutrition.

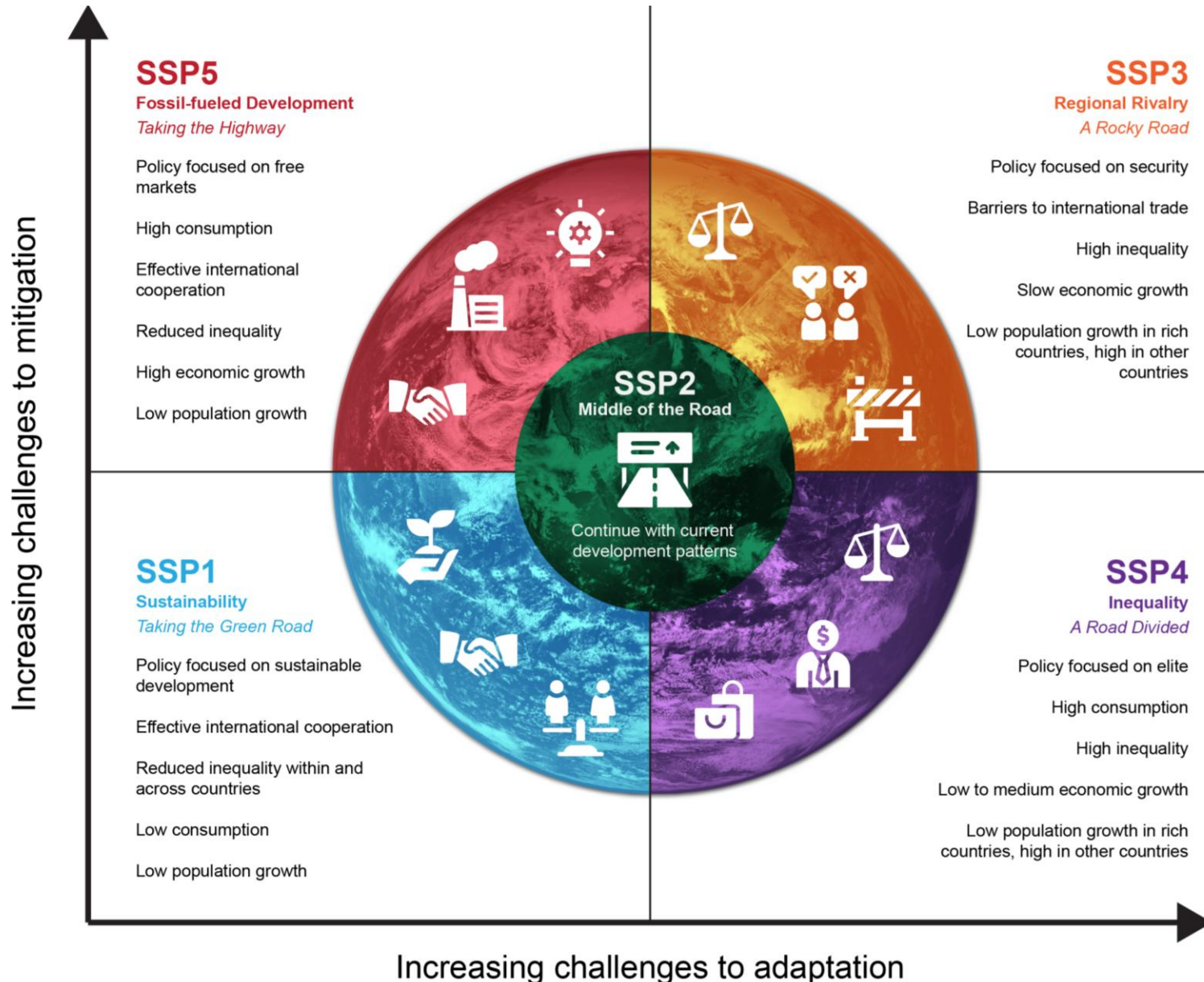


**SSP: Shared Socioeconomic Pathways**

Limited adaptation (failure to proactively adapt; low investment in health systems); incomplete adaptation (incomplete adaptation planning; moderate investment in health systems); proactive adaptation (proactive adaptation management; higher investment in health systems)

The SSP1 pathway illustrates a world with low population growth, high income, and reduced inequalities, food produced in low GHG emission systems, effective land use regulation and high adaptive capacity (i.e., low challenges to adaptation). The SSP3 pathway has the opposite trends.

**Shared Socioeconomic Pathways (SSPs)** are narratives that describe potential future global developments relevant to climate change, considering factors like population growth, economic development, and technological progress.



## Search for a sustainable society @ 2025

In today's world, problems that pose **challenges to a sustainable society are not separate**. Rather, they **interact in two gigantic complex adaptive systems: the biosphere system and the human socio-economic system**.

The negative manifestations of these interactions are often referred to as 'the human predicament', and determining how to prevent it from generating a global collapse is perhaps *the* foremost challenge confronting humanity.

The human predicament arises from overpopulation, excessive resource consumption, and reliance on environmentally harmful technologies and socio-economic systems designed to sustain the aggregate consumption of Homo sapiens.

Ehrlich PR, Ehrlich AH. Proc R Soc B, 2013, 280: 20122845.<http://dx.doi.org/10.1098/rspb.2012.2845>

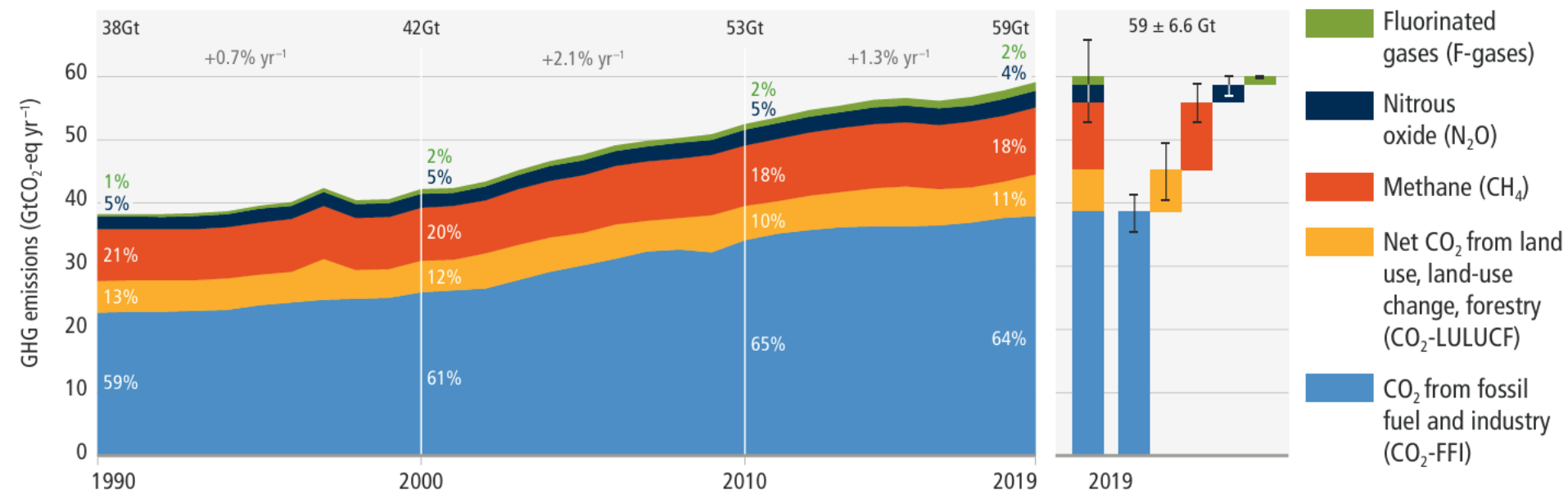
The emerging science of early-warning signals offers valuable insights into when systems are approaching critical thresholds or losing their ability to withstand changing conditions. Indicators such as “critical slowing down,” rising variance, and flickering between alternative states can signal heightened vulnerability. However, for these signals to inform effective policy action, they must provide sufficient lead time for societal response and intervention. Importantly, system inertia—such as that observed in the climate system—must be factored into assessments of how quickly society can react, as delayed responses may render even timely warnings ineffective.

Such a process allows the ecosystem to tolerate perturbations and shocks and to continue functioning under changing abiotic conditions.

The application of the precautionary principle dictates that the planetary boundary is set at the “safe” end of the zone of uncertainty. This does not mean that transgressing a boundary will instantly lead to an unwanted outcome, but that the farther the boundary is transgressed, the higher the risk of regime shifts, destabilized system processes, or erosion of resilience and the fewer opportunities to prepare for such changes.

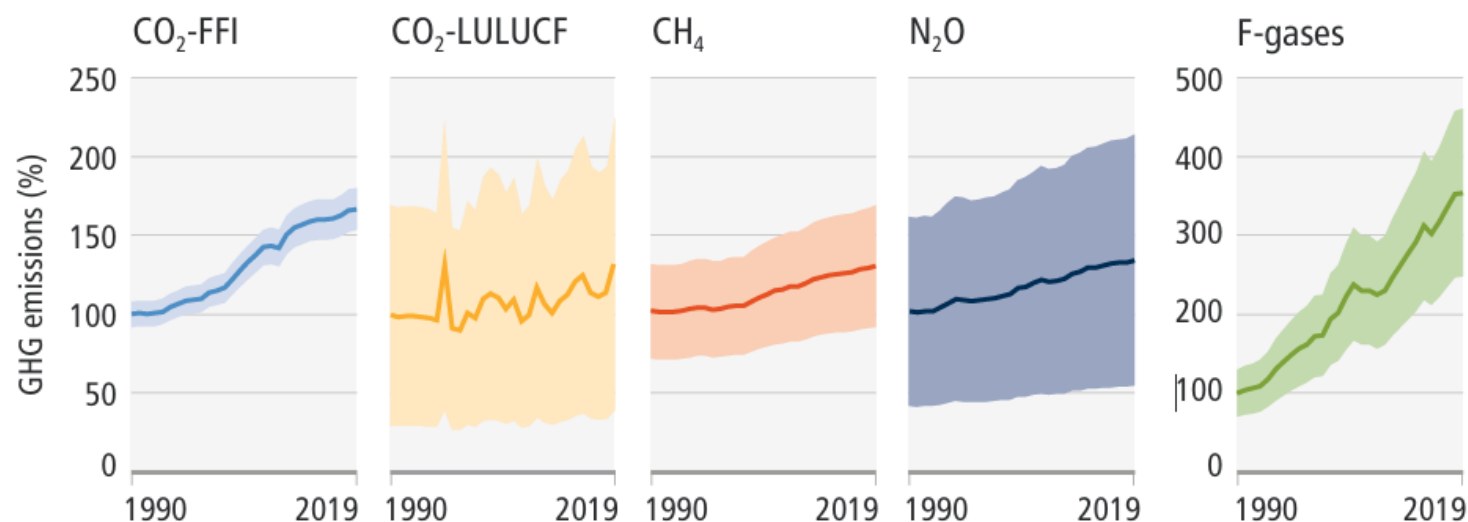
# Global net anthropogenic emissions have continued to rise across all major groups of greenhouse gases.

a. Global net anthropogenic GHG emissions 1990–2019<sup>(5)</sup>



The solid line indicates central estimate of emissions trends. The shaded area indicates the uncertainty range.

The solid line indicates central estimate of emissions trends. The shaded area indicates the uncertainty range.



There is a strong link between sustainable development, vulnerability and climate risks. Limited economic, social and institutional resources often result in high vulnerability and low adaptive capacity, especially in developing countries (medium confidence).

Several response options deliver both mitigation and adaptation outcomes, especially in human settlements, land management, and in relation to ecosystems. However, land and aquatic ecosystems can be adversely affected by some mitigation actions, depending on their implementation. Coordinated cross-sectoral policies and planning can maximise synergies and avoid or reduce trade-offs between mitigation and adaptation. {3.7, 4.4, 13.8, 17.3; AR6 WGII}

Starting in 1990, the **Intergovernmental Panel on Climate Change (IPCC)** has used the **Global Warming Potential (GWP)** to allow comparisons of the global warming impacts of different gases.

The **Global Warming Potentials (GWP)** is a measure of how much energy the emission of 1 ton of a gas will absorb over a given period, relative to the emission of 1 ton of carbon dioxide (CO<sub>2</sub>). The larger the GWP, the more that a given gas warms the Earth compared to CO<sub>2</sub> over that period. The period usually used for GWPs is 100 years.

GWPs are a quantified measure of the globally averaged relative radiative forcing impacts of particular greenhouse gases in the atmosphere. It is defined as the cumulative radiative forcing – both direct and indirect effects – integrated over time from the emission of a unit mass of gas relative to some reference gas (IPCC 1996).

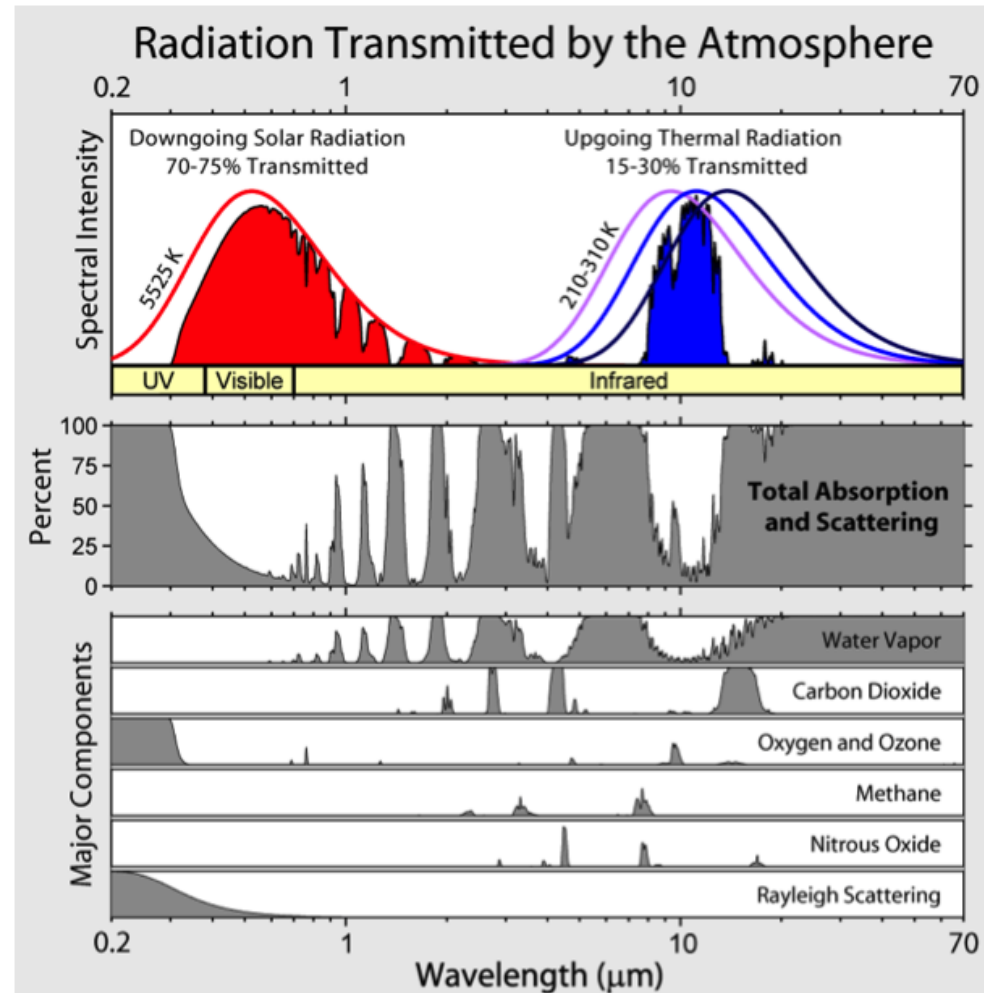
<https://ghginstitute.org/2010/06/28/what-is-a-global-warming-potential/>

<https://www.epa.gov/ghgemissions/understanding-global-warming-potentials>

Three key factors determine the GWP value of a GHG:

- ✓ where along the electromagnetic spectrum (i.e., wavelengths) the gas absorbs radiation, and
- ✓ the ability to absorb IR radiation,
- ✓ the atmospheric lifetime of the gas.

We typically only use GWP values for gases that have a long atmospheric lifetime (i.e., in years), as only these gases last long enough in the atmosphere to mix evenly and spread throughout the atmosphere to form a relatively uniform concentration. GWP values are meant to be “global,” as the name implies. If a type of gas is short-lived and does not have a global concentration because it is destroyed too quickly to mix evenly throughout the atmosphere, then it typically is not assigned a GWP value.



<https://ghginstitute.org/2010/06/28/what-is-a-global-warming-potential/>

## Which Gas Has the Highest Atmospheric Lifetime?

When comparing the four gases:

**CO<sub>2</sub>:** A significant fraction remains for centuries to millennia, and some for tens of thousands of years.

**CH<sub>4</sub>:** About 12 years.

**N<sub>2</sub>O:** About 109–132 years.

**CFCs:** 16 to more than 500 years (some types over a millennium).

Greenhouse Gas (GHG)	Atmospheric Lifetime (yrs)	Global Warming Potential (GWP)	Primary Current Sources	High GWP gases
Carbon dioxide (CO <sub>2</sub> )	50-200	1	Fossil fuel use, land use, cement	
Methane (CH <sub>4</sub> )	12±3	21	Fossil fuel use, agriculture	
Nitrous oxide (N <sub>2</sub> O)	120	310	Mostly agriculture, ~1/3 are anthropogenic	
Hydrofluorocarbons (HFCs)	1.5 to 209	150 to 11,700	Alternative to ozone depleting substances	
Perfluorocarbons (PFCs)	2,600 to 50,000	6,500 to 9,200	Primary aluminum production; semiconductor manufacturing	
Sulfur Hexafluoride (SF <sub>6</sub> )	3,200	23,900	Used in electric power transmission, magnesium and semiconductor industries	

<https://www.global-climate-change.org.uk/6-5-2.php>

The Kyoto Protocol fixed the use of GWP values published by the IPCC in 1996 in its Second Assessment Report. Since then, the IPCC has updated its GWP values four times, in 2001, 2007, 2013, and 2021. The result has been a proliferation of GWP values out there that leads to a lot of confusion.

The **International Standard Organisation (ISO)** and relevant communities use the term “**GWP**” as an **impact category** to refer to the embodied greenhouse gases of a specific product or product-level GHG emission intensities (see, e.g., ISO 21930:2017). This specific use of GWP by the EPD (Environmental Product Declarations) community refers to the total greenhouse gas emissions directly associated with the production of a product, including the upstream activities of extraction and transport of raw materials.

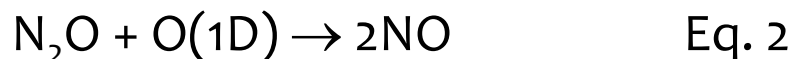
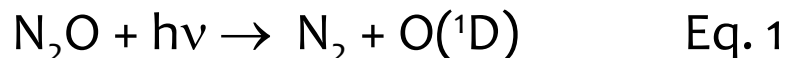
### Why do GWPs change over time?

EPA and other organizations will update the GWP values they use occasionally. This change can be due to updated scientific estimates of the energy absorption or lifetime of the gases or to changing atmospheric concentrations of GHGs that result in a change in the energy absorption of 1 additional ton of a gas relative to another.

Nitrous oxide (N<sub>2</sub>O) has its maximum concentration in the middle stratosphere at the same site as ozone. N<sub>2</sub>O is a long-lived stratospheric ozone-depleting substance and greenhouse gas with a current atmospheric lifetime of  $116 \pm 9$  years. The atmospheric N<sub>2</sub>O has increased by more than 20% from 270 parts per billion (ppb) in 1750 to 331 ppb in 2018. Two key biochemical processes—nitrification and denitrification—control N<sub>2</sub>O production in both terrestrial and aquatic ecosystems and are regulated by multiple environmental and biological factors, including temperature, water and oxygen levels, acidity, and substrate availability.

[Nature, 2020, 586, 248–256]

N<sub>2</sub>O can be decomposed in the middle stratosphere through photolysis to N<sub>2</sub> and O(<sup>1</sup>D) (Eq. 1). A minor fraction of N<sub>2</sub>O reacts with O(<sup>1</sup>D) to form NO (Eq. 2) at lower altitudes where photolysis occurs. This reaction is the principal source of reactive nitrogen (NO<sub>x</sub>), which participates in a catalytic cycle with O<sub>3</sub>, whereby a single NO molecule can destroy 10<sup>3</sup>–10<sup>5</sup> ozone molecules before being converted into a less reactive form. [Coord. Chem. Rev.387 (2019)436–449]



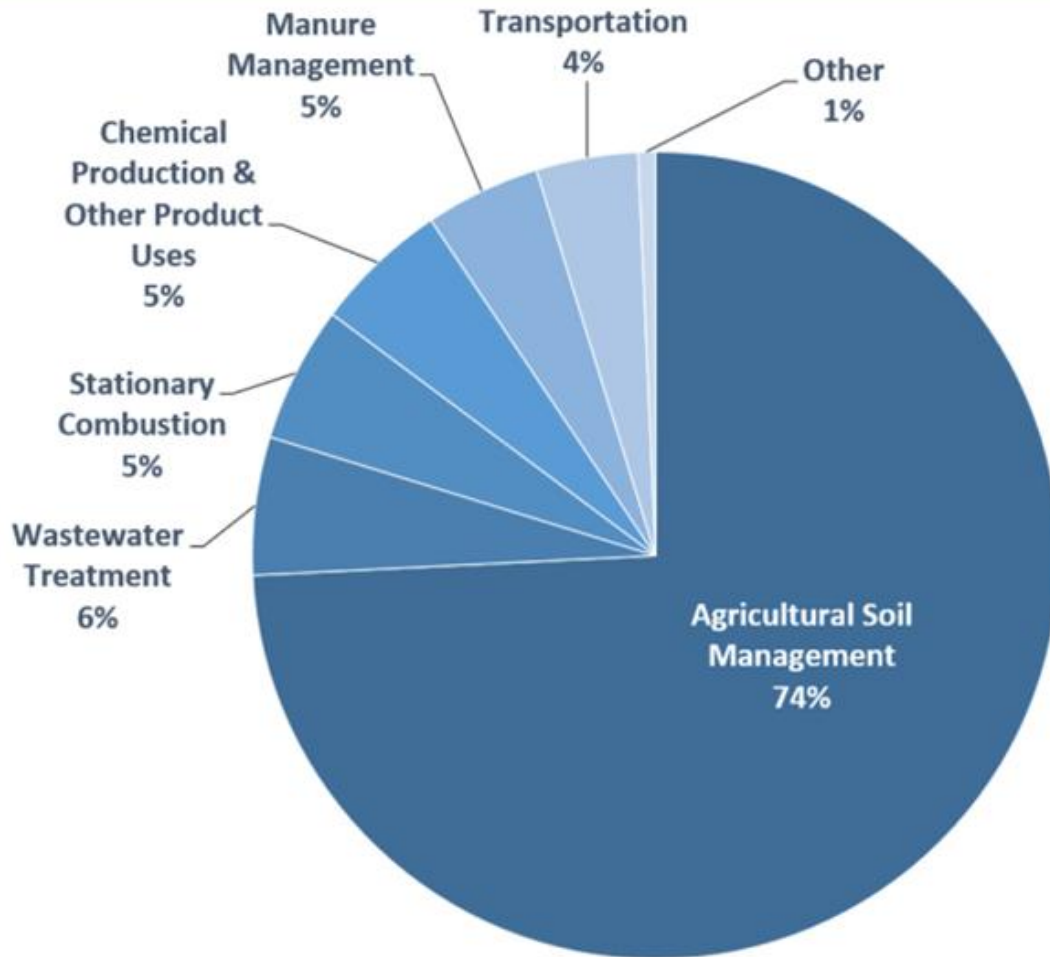
O(<sup>1</sup>D) refers to the first excited state of an oxygen atom

The relative contributions of various ODSs to ozone layer depletion are often quantified by the ozone depletion potential (ODP). An ODP relates the amount of stratospheric ozone destroyed by the release of a unit mass of a chemical at Earth's surface to the amount destroyed by the release of a unit mass of chlorofluorocarbon 11 (CFC-11). ODPs are widely used for policy formulation because of their simplicity in quantifying the relative ozone-destroying capabilities of compounds. Nitrogen oxides (NO<sub>x</sub>), which include NO and NO<sub>2</sub>, are known to be involved in ozone chemistry, but are not typically referred to by their ODP values.



A single NO molecule can destroy 10<sup>3</sup>–10<sup>5</sup> ozone molecules before being converted into a less reactive form.

## 2020 U.S. Nitrous Oxide Emissions, By Source

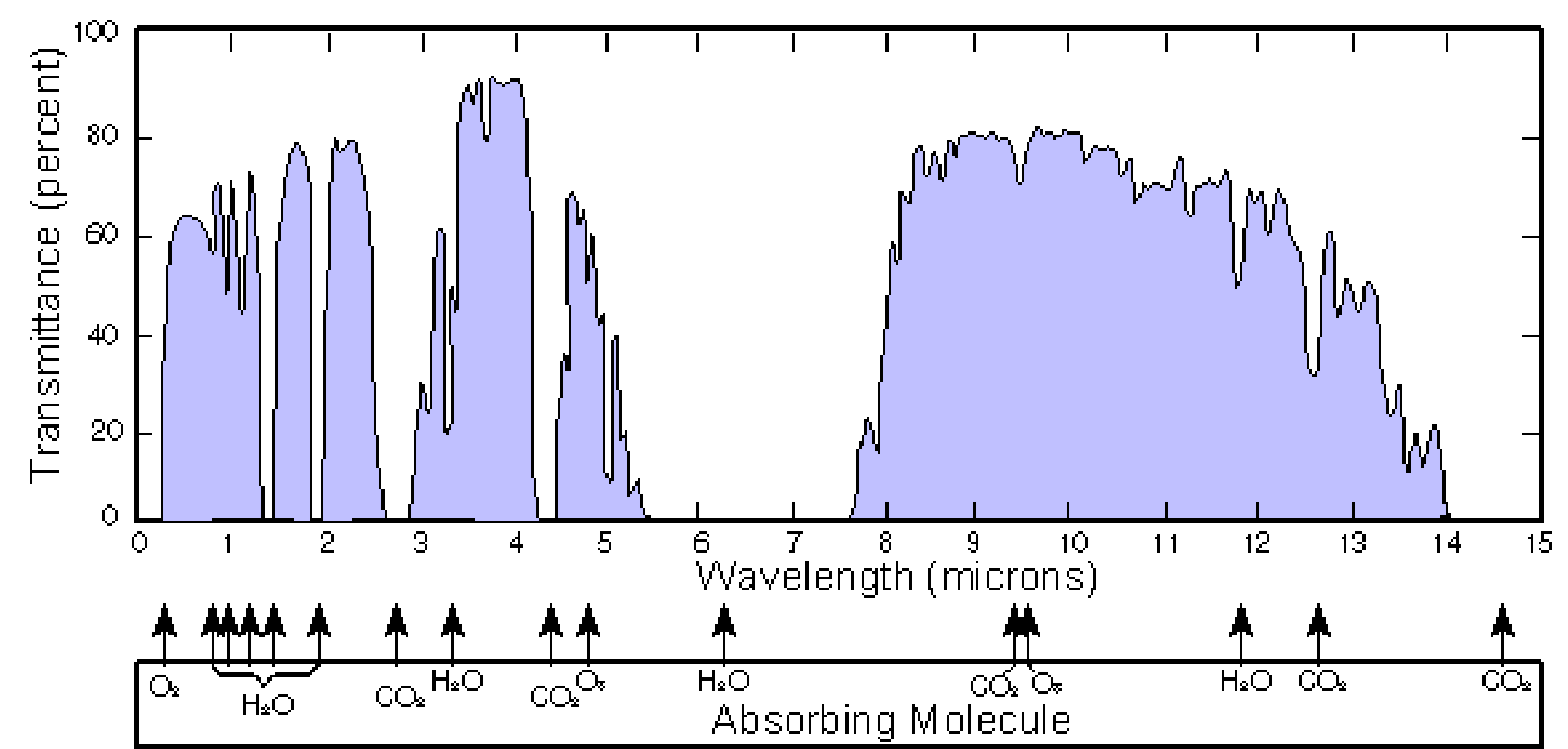


<https://prepp.in/news/e-492-nitrous-oxide-as-greenhouse-gas-environment-notes>

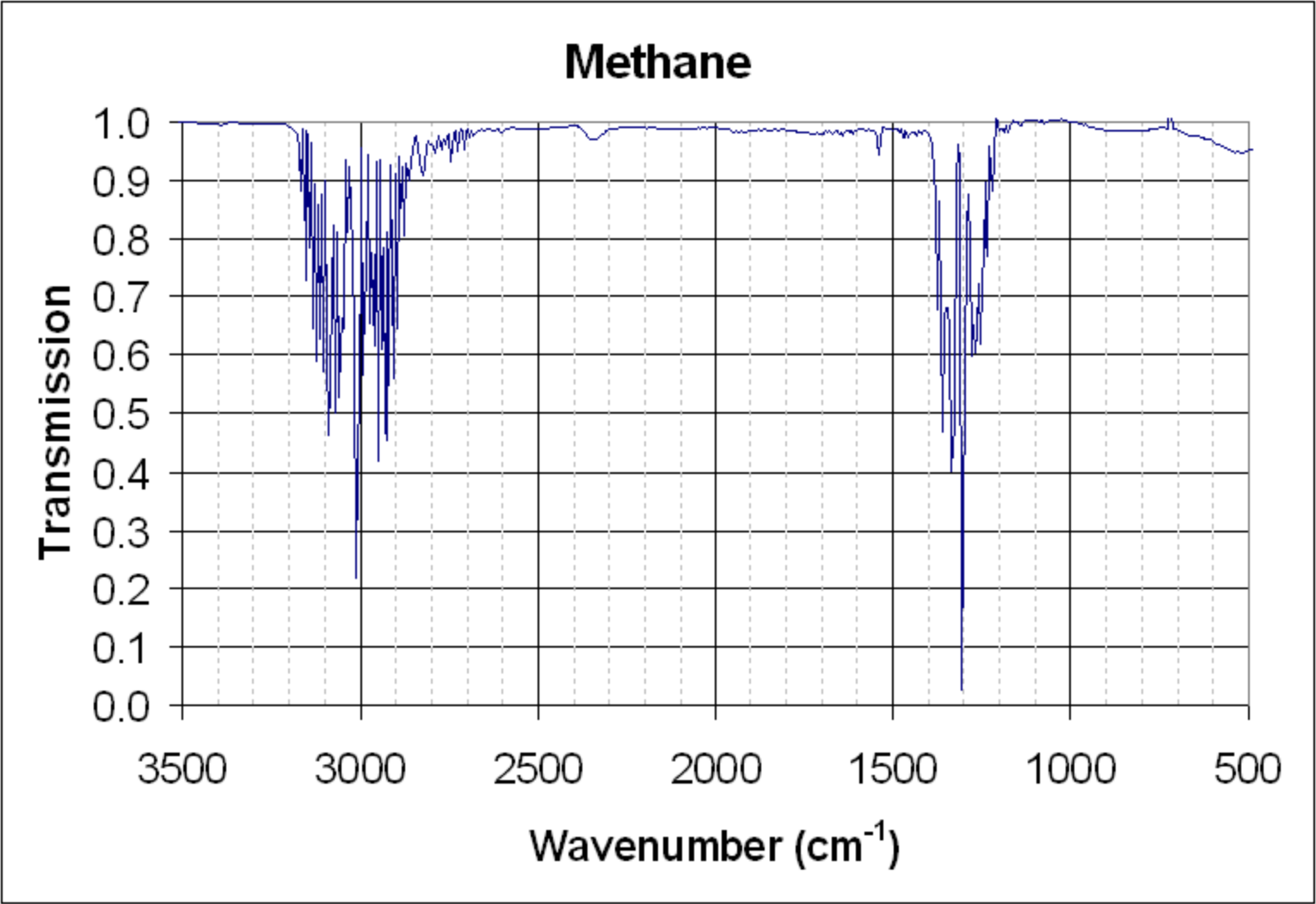
Nitrous oxide has 298 times the atmospheric heat-trapping ability of carbon dioxide (CO<sub>2</sub>) per molecule over 100 years.

However, due to its low concentration (less than 1/1,000 of that of CO<sub>2</sub>), its contribution to the greenhouse effect is less than one-third that of CO<sub>2</sub>, and also less than water vapour and methane.

Both **water** and **CO<sub>2</sub>** absorb with nearly 100% in their frequency range. In order to absorb more light, one has to absorb in other frequency ranges.



CH<sub>4</sub> absorbs in a frequency range that is covered neither by water nor by CO<sub>2</sub>.



## **Why Methane has higher potential:**

CH<sub>4</sub> has a tetrahedral molecular shape with four C–H bonds arranged symmetrically around a central carbon atom. Although the molecule is symmetric, it can vibrate in ways that change its dipole moment—a key requirement for absorbing infrared (IR) radiation.

**Methane has several vibrational modes (e.g., bending, stretching) that are IR-active. These include:**

**Asymmetric C–H stretching**

**Scissoring (bending) of H–C–H angles**

Due to multiple IR active vibrational modes, the radiative efficiency of methane is higher than the other gases. These vibrations occur at wavelengths that coincide with Earth's emitted IR radiation, especially around 7.6 μm, which is within the “atmospheric window” (a range where Earth cools effectively), which lies within the atmospheric window (8–12 μm)—a crucial region where Earth emits infrared radiation and where few other gases absorb efficiently. This makes methane particularly effective at trapping heat that would otherwise escape to space. CH<sub>4</sub> partially closes that window by absorbing heat in this otherwise transparent region.

## Radiation Absorption: N<sub>2</sub>O vs. CO<sub>2</sub> and CH<sub>4</sub>

N<sub>2</sub>O absorbs **infrared radiation** differently compared to CO<sub>2</sub> and methane (CH<sub>4</sub>) due to differences in their molecular structures and vibrational modes:

- **CO<sub>2</sub>** predominantly absorbs infrared radiation near **15 μm**, a critical part of the thermal spectrum emitted by Earth's surface. Its relatively simple molecular structure limits the number of vibrational modes, and thus, the range of infrared wavelengths it can absorb.
- **CH<sub>4</sub>**, with a more complex bonding structure, absorbs infrared radiation at multiple wavelengths, notably around **7.66 μm**. This enables CH<sub>4</sub> to trap significantly more heat per molecule than CO<sub>2</sub>. However, CH<sub>4</sub> has a shorter atmospheric lifetime, which moderates its long-term impact.
- **N<sub>2</sub>O** exhibits strong infrared absorption in the **4.5 to 5.3 μm** range—regions not effectively covered by water vapour, CO<sub>2</sub>, or CH<sub>4</sub>. Due to its molecular complexity and multiple vibrational modes, N<sub>2</sub>O efficiently captures thermal energy across a broader section of the infrared spectrum, playing a unique and complementary role in Earth's greenhouse effect.

## Reading material:

1. Etminan, M., et al. . Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, 43(24), pp.12-614.

### Why Methane has higher potential:

Methane has a tetrahedral molecular shape with four C–H bonds arranged symmetrically around a central carbon atom. Although the molecule is symmetric, it can vibrate in ways that change its dipole moment—a key requirement for absorbing infrared (IR) radiation.

**Methane has several vibrational modes (e.g., bending, stretching) that are IR-active. These include:**

- **Asymmetric C–H stretching**
- **Scissoring (bending) of H–C–H angles**

Due to multiple IR active vibrational mode the radiative efficiency of methane is higher than the other gases. These vibrations occur at wavelengths that coincide with Earth's emitted IR radiation, especially around 7.6  $\mu\text{m}$ , which is within the “atmospheric window” (a range where Earth cools effectively) which lies within the atmospheric window (8–12  $\mu\text{m}$ )—a crucial region where Earth emits infrared radiation and where few other gases absorb efficiently. This makes methane particularly effective at trapping heat that would otherwise escape to space.  $\text{CH}_4$  partially closes that window by absorbing heat in this otherwise transparent region.

In contrast,  $\text{CO}_2$  is a linear molecule ( $\text{O}=\text{C}=\text{O}$ ) with fewer IR-active modes. Its main IR absorption occurs at  $\sim 15 \mu\text{m}$ , which is outside the atmospheric window and overlaps significantly with water vapour absorption. Moreover, the  $\text{CO}_2$  absorption bands are already partly saturated in the atmosphere, meaning that additional  $\text{CO}_2$  traps less incremental heat. While water vapor is the most abundant greenhouse gas, its concentration is temperature-dependent and controlled by feedback, not direct emissions. Moreover,  $\text{H}_2\text{O}$  mainly absorbs IR in regions that are already saturated, and its short atmospheric lifetime (hours to days) limits its long-term warming potential. Further due to the smaller number of the IR active bonds the per molecule absorption of IR for water is much lower than methane. In case of  $\text{NO}_x$ , due to lower IR active bonds and less per molecule absorption capacity,  $\text{NO}_x$  act as a secondary greenhouse gas by forming ozone a stronger absorber of UV light. Hence,  $\text{CH}_4$ , though present in smaller quantities, stays in the atmosphere for about 12 years and is far more efficient per molecule in absorbing and re-emitting IR radiation.

per molecule, methane can absorb and re-radiate more thermal energy than  $\text{CO}_2$ . Although  $\text{CO}_2$  is more abundant and longer-lived, methane's molecular structure and unique spectral properties give it a much higher global warming potential—about 28–36 times more than  $\text{CO}_2$  over a 100-year timescale (IPCC AR6).

# Global warming potential (GWP) values relative to CO<sub>2</sub>

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon		
		Second Assessment Report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Carbon dioxide	CO <sub>2</sub>	1	1	1
Methane	CH <sub>4</sub>	21	25	28
Nitrous oxide	N <sub>2</sub> O	310	298	265

## Substances controlled by the Montreal Protocol

CFC-11	CCl <sub>3</sub> F	3,800	4,750	4,660
CFC-12	CCl <sub>2</sub> F <sub>2</sub>	8,100	10,900	10,200
CFC-13	CClF <sub>3</sub>		14,400	13,900
CFC-113	CCl <sub>2</sub> FOCClF <sub>2</sub>	4,800	6,130	5,820
CFC-114	CClF <sub>2</sub> CClF <sub>2</sub>		10,000	8,590
CFC-115	CClF <sub>2</sub> CF <sub>3</sub>		7,370	7,670
Halon-1301	CBrF <sub>3</sub>	5,400	7,140	6,290
Halon-1211	CBrClF <sub>2</sub>		1,890	1,750
Halon-2402	CBrF <sub>2</sub> CBrF <sub>2</sub>		1,640	1,470
Carbon tetrachloride	CCl <sub>4</sub>	1,400	1,400	1,730
Methyl bromide	CH <sub>3</sub> Br		5	2
Methyl chloroform	CH <sub>3</sub> CCl <sub>3</sub>	100	146	160

efaidnbmnnnibpcajpcgiclfendmk  
aj/https://ghgprotocol.org

The following table includes the 100-year time horizon global warming potentials (GWP) relative to CO<sub>2</sub>. This table is adapted from the IPCC Fifth Assessment Report, 2014 (AR5)

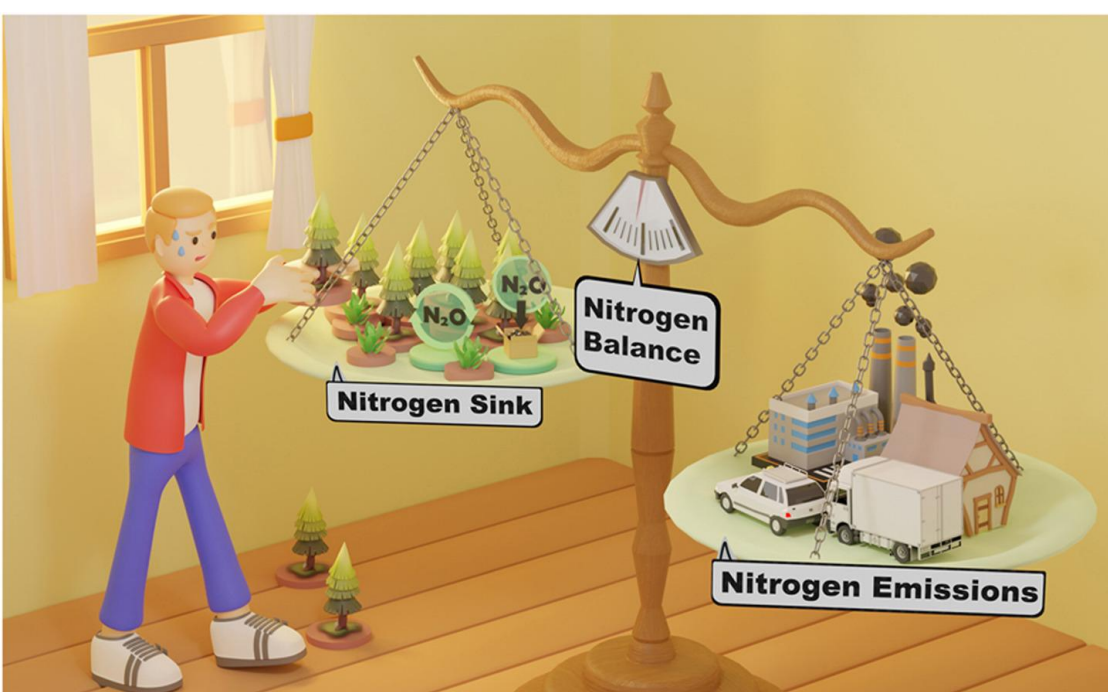
Nitrous oxide ( $\text{N}_2\text{O}$ ) is the third most important long-lived GHG after carbon dioxide ( $\text{CO}_2$ ) and methane.  $\text{N}_2\text{O}$  is also one of the stratospheric ozone-depleting substances (ODS) that are being released more of it into the atmosphere than previously thought. (Nature Climate Change; 2019, 9, 993–998).

With a global warming potential roughly 300 times greater than  $\text{CO}_2$ ,  $\text{N}_2\text{O}$  can be a major contributor to the greenhouse gas footprint (Water Sci Technol (2013) 67 (10): 2350–2355.)  $\text{N}_2\text{O}$  is still growing at a rate of  $0.2\text{--}0.3\% \text{ y}^{-1}$ . [PNAS, 2019, 116, 12822–12827]

A modified distribution of  $\text{N}_2\text{O}$  in the stratosphere can be of importance for ozone chemistry.  $\text{N}_2\text{O}$  is inert in the troposphere and decays only in the stratosphere. Thus, changes in the exchange between troposphere and stratosphere can also affect the stratospheric sink of  $\text{N}_2\text{O}$ , and consequently its atmospheric lifetime. The projected increase in stratospheric  $\text{N}_2\text{O}$  could reduce the ozone shield by about a factor of 2. The lifetime of  $\text{N}_2\text{O}$  is proposed to be  $116 \pm 9$  years and it is estimated that it takes around 120 years to remove 63% of its initial emission. [J. Geophys. Res. Atmos., 120, 5693–5705]

$\text{N}_2\text{O}$  emission currently is the single most important  $\text{O}_3$ -depleting emission and is expected to remain the largest in the 21st century. Science, 2009, 326, 123-125

- Nitrous oxide ( $\text{N}_2\text{O}$ ) is relatively stable and unreactive in the troposphere, the lowest layer of the atmosphere, and it primarily decays in the stratosphere, the layer above.
- The troposphere is characterised by turbulence and weather phenomena, but  $\text{N}_2\text{O}$  is largely unreactive at the typical temperatures and pressures found there.
- The stratosphere contains the ozone layer, which absorbs ultraviolet (UV) radiation from the sun. This provides the energy needed to break down  $\text{N}_2\text{O}$  molecules, causing them to decay.

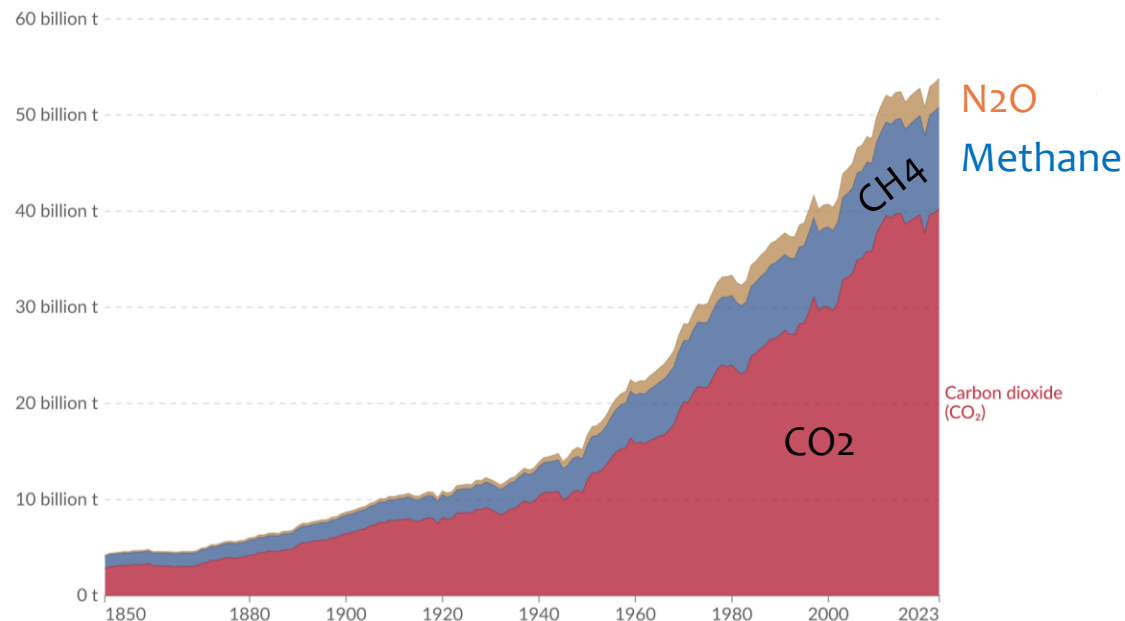


From 1970 to 2018, the annual global anthropogenic  $\text{N}_2\text{O}$  emissions increased by 64%—about 3.6 teragrams (Tg); agricultural sources primarily accounted for 78% of this increment.

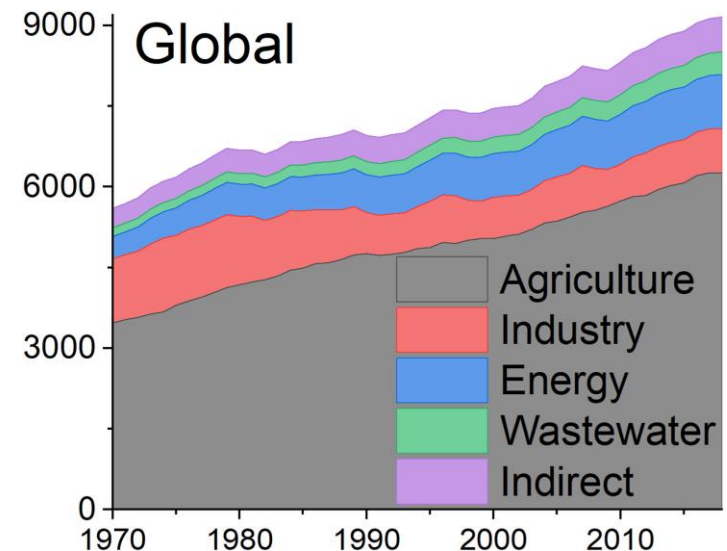
## Greenhouse gas emissions by gas, World, 1850 to 2023

Our World in Data

Greenhouse gas emissions<sup>1</sup> from all sources, including agriculture and land-use change. They are measured in tonnes of carbon dioxide-equivalents<sup>2</sup> over a 100-year timescale.



## Yearly average global $\text{N}_2\text{O}$ budgets between 2007 and 2016



# GLOBAL N<sub>2</sub>O BUDGET

## ANTHROPOGENIC SOURCES

## CHANGE IN ATMOSPHERIC ABUNDANCE

## NATURAL SOURCES

7.3  
(4.2 to 11.4)

4.3  
(3.8 to 4.8)

9.7  
(8.0 to 12.0)

4.2  
(2.7 to 6.3)

0.6  
(0.5 to 0.8)

1.0  
(0.8 to 1.1)

1.3  
(0.7 to 2.2)

0.6  
(-0.3 to 2.3)

6.0  
(5.2 to 6.6)

3.4  
(2.5 to 4.3)

13.5  
(12.4 to 14.6)

Agriculture and waste water

Biomass burning

Fossil fuel and industry

Indirect emission

Other fluxes

Land

Oceans

Atmospheric chemical sink

### FLUX OF N<sub>2</sub>O BY SOURCE

in Teragrams of Nitrogen per year (Tg N or million metric tons yr<sup>-1</sup>) for the decade of 2007-2016

Anthropogenic sources

Natural sources

Natural sinks

Other fluxes: Lightning and atmospheric production, soil surface sink, climate change, increasing CO<sub>2</sub>, deforestation