Course 2024–2025 in Sustainable Finance
Lecture 6. Biodiversity

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[1]The opinions expressed in this presentation are those of the authors and are not meant to represent the opinions or official positions of Amundi Asset Management.

Agenda

- Lecture 1: Introduction
- Lecture 2: ESG Scoring
- Lecture 3: Impact of ESG Investing on Asset Prices and Portfolio Returns
- Lecture 4: Sustainable Financial Products
- Lecture 5: Impact Investing
- **Lecture 6: Biodiversity**
- Lecture 7: Engagement & Voting Policy
- Lecture 8: Extra-financial Accounting
- Lecture 9: Awareness of Climate Change Impacts
- Lecture 10: The Ecosystem of Climate Change
- Lecture 11: Economic Models & Climate Change
- Lecture 12: Climate Risk Measures
- Lecture 13: Transition Risk Modeling
- Lecture 14: Climate Portfolio Construction
- Lecture 15: Physical Risk Modeling
- Lecture 16: Climate Stress Testing & Risk Management

Biodiversity & ESG

An important issue in the ESG financial community:

- SFDR's mandatory **principal adverse impact** indicator on biodiversity (PAI 7)
- Sixth economic objective of the **EU green taxonomy** (protection and restoration of biodiversity and ecosystems)
- ESRS E4 category of the **CSRD** (biodiversity and ecosystems)

Definition

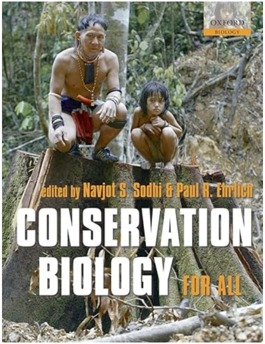
Definition

Biodiversity, or biological **diversity**, refers to the variety and variability of life on Earth in all its many manifestations

- Biodiversity is a broad, unifying concept that encompasses all forms, levels, and combinations of natural variation at all levels of biological organization (Gaston and Spicer, 2004)
- It includes genetic diversity within species, the diversity of species in different habitats, and the diversity of ecosystems themselves
- Biodiversity encompasses all living organisms, from the smallest bacteria to the largest mammals, and the complex relationships and interactions among them

Definition

Figure 1: Biodiversity ≈ Conservation Biology



Sodhi, N. S. and Ehrlich, P. R. (2010). *Conservation Biology for All*. Oxford University Press, 351 pages.

Key components of biodiversity

Genetic diversity

- Variety of genes within a species (*e.g.*, rice)
- Essential for the survival and adaptability of species
- Evolution in response to changing conditions

Organismal diversity

- Species diversity (species richness)
- Relative abundance of each species (species evenness)
- Variation in the distribution of species in space (beta diversity or species density)

Ecological diversity

- Ecosystem diversity
- Habitats, biological communities, and ecological processes
- forests, grasslands, wetlands, deserts, marine environments, etc.

Key components of biodiversity

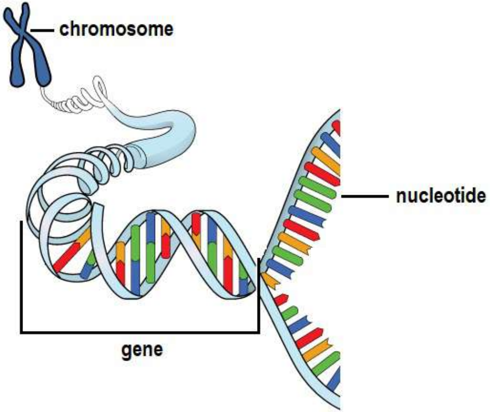
Table 1: Elements of biodiversity

Ecological diversity	Genetic diversity	Organismal diversity
Biogeographic realms		Domains or Kingdoms
Biomes		Phyla
Provinces		Families
Ecoregions		Genera
Ecosystems		Species
Habitats		Subspecies
Populations	Populations	Populations
	Individuals	Individuals
	Chromosomes	
	Genes	
	Nucleotides	

Source: Gaston (2010).

Genetic diversity

Figure 2: Nucleotides, genes, and chromosomes



Source: `blog.myheritage.com/2018/02/dna-basics-chapter-3-dna-expression`.

Genetic diversity

- Genetic (or genomic) diversity can be assessed at different structural levels: nucleotides, genes, or chromosomes
- Nucleotide differences: adenine (A), cytosine (C), guanine (G), and thymine (T)
- Allelic diversity (average number of alleles per locus)
- Gene diversity or polymorphism (proportion of polymorphic loci across the genome)
- Heterozygosity

Genetic diversity

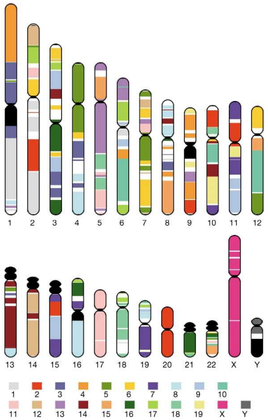
Genetic diversity measurement

- Number of genes
- Genome size (or C-value)
- The **C-value** is the amount of DNA contained in a haploid set of chromosomes
- It is typically measured in picograms (pg) or base pairs (bp)
- A **base pair** is the basic unit of DNA sequence and corresponds to two nucleotides that combine to form the DNA double helix
- The conversion between C-value and base pairs uses the following correspondence: 1 picogram is equal to 978 Mbp (million base pairs)

Genetic diversity

Table 2: Human genome sequencing

Statistics	GRCH38
Base pairs (Gbp)	2.92
Number of genes	**60 090**
Number of protein-coding genes	19 890
% of repeats	51.89
Statistics	T2T-CHM13
Base pairs (Gbp)	3.05
Number of genes	**63 494**
Number of protein-coding genes	19 969
% of repeats	53.94



Source: https://www.nature.com/articles/35057062.

Genetic diversity

Table 3: Genetic diversity of some organisms

Organism	C-value (in pg)	Base pairs (in Mbp)	Genes ($\times 10^3$)	Chromosomes ($2n$ or kn)
Mycoplasma (bacterium)		0.580	0.45 – 0.70	1*
Haemophilus influenzae (bacterium)		1.8	1.750	1*
Escherichia coli (bacterium)		4.6	4 – 5	1*
Drosophila melanogaster (fruit fly)	0.17	180	13 – 17	8
Arabidopsis thaliana (mustard plant)	0.14	135	27	10
Caenorhabditis elegans (nematode)	0.10	100	21	12
Saccharomyces cerevisiae (yeast)	0.02	12	6	16
Zea mays (corn)	2.30	2 300	32 – 40	20
Oryza sativa (rice)	0.40	430	32 – 50	24
Musmusculus (mouse)	2.60	2 700	20 – 25	40
Rattus norvegicus (brown rat)	2.75	2 700	20 – 25	42
Homo sapiens (human)	3.20	3 050	20	46
Solanum tuberosum (tetraploid potato)	3.50	3 400	39 – 45	48*
Fragaria ananassa (octoploid strawberry)	2.50	2 500	35 – 45	56*
Canis lupus familiaris (dog)	2.80	2 800	20	78
Agrodiaetus shahrami (butterfly)	0.75	750	12 – 14	100 – 268*
Ophioglossum reticulatum (polyploid fern)	6.25	6 200	30 – 50	1 440*

Genetic diversity

- The number of chromosomes in butterflies can vary greatly from species to species
- Most butterfly species have between 28 and 100 chromosomes
- Common butterflies such as the Monarch (*Danaus plexippus*) have 30 chromosomes
- The *Agrodiaetus* butterfly has 268 chromosomes

Figure 3: Blue Morpho butterfly

~~Butterflies form a species~~

Species diversity

Definition

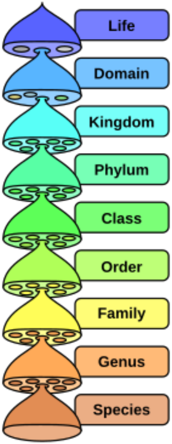
A biological species is a group of organisms that can reproduce with one another in nature and produce fertile offspring. Species are defined by the fact that they are reproductively isolated from other groups, meaning that organisms within one species cannot successfully reproduce with those of another species.

Source: https://www.nature.com/scitable/definition/species-312.

Species diversity

- Domain
- Kingdom
- phylum (or division)
- Class
- Order
- Family
- Genus
- Species

- Magn(order)
- Super(order)
- Grand(order)
- Mir(order)
- Order
- Sub(order)
- Infra(order)
- Parv(order)



- Domain: *Eukarya*
- Kingdom: *Animalia*
- Phylum: *Chordata*
- Class: *Mammalia*
- Order: *Primates*
- Family: *Hominidae* (great apes)
- Genus: *Homo*
- Species: ***Homo sapiens***, *Homo neanderthalensis*, *Homo erectus*, and *Homo habilis*

Species diversity

Robert May (1988): ***How Many Species are There on Earth?***

*"If some alien version of the Starship Enterprise visited Earth, what might be the visitors' first question? I think it would be: How many distinct life forms — species — does your planet have? Embarrassingly, our best-guess answer would be in the range of 5 to 10 million eukaryotes (never mind the viruses and bacteria), but we could defend numbers exceeding **100 million, or as low as 3 million**." (May, 2010).*

*"In 2010, Robert May pointed out an embarrassing truth about modern science. Even as we invest huge amounts of time, money, and effort to find life on other planets, we still do not know how much life (i.e., how many species) is on our own. Although 'do not know' might sound like hyperbole, estimates have ranged wildly, **from 2 million to 3 trillion**." (Wiens, 2023).*

Species diversity

Table 4: Currently catalogued and predicted total number of species on Earth and in the ocean

Species	Earth			Ocean		
	Catalogued	Predicted	± SE	Catalogued	Predicted	± SE
Eukaryotes	1 233 500	8 740 000	1 300 000	193 756	2 210 000	182 000
Animalia	953 434	7 770 000	958 000	171 082	2 150 000	145 000
Chromista	13 033	27 500	30 500	4 859	7 400	9 640
Fungi	43 271	611 000	297 000	1 097	5 320	11 100
Plantae	215 644	298 000	8 200	8 600	16 600	9 130
Protozoa	8 118	36 400	6 690	8 118	36 400	6 690
Prokaryotes	10 860	10 100	3 630	653	1 320	436
Archaea	502	455	160	1	1	0
Bacteria	10 358	9 680	3 470	652	1 320	436
Total	1 244 360	**8 750 000**	1 300 000	194 409	2 210 000	182 000

Source: Mora *et al.* (2011).

Species diversity

- `www.ncbi.nlm.nih.gov/taxonomy`
- `www.fws.gov/explore-taxonomic-tree`

Try the following species: *Apis mellifera*, *Homo sapiens*, *Rosa*, *Solanum tuberosum* and *Zea mays*

Ecological diversity

- Biogeographic realm
- Biome
- Province
- Ecoregion
- Ecosystem
- Habitat
- Population

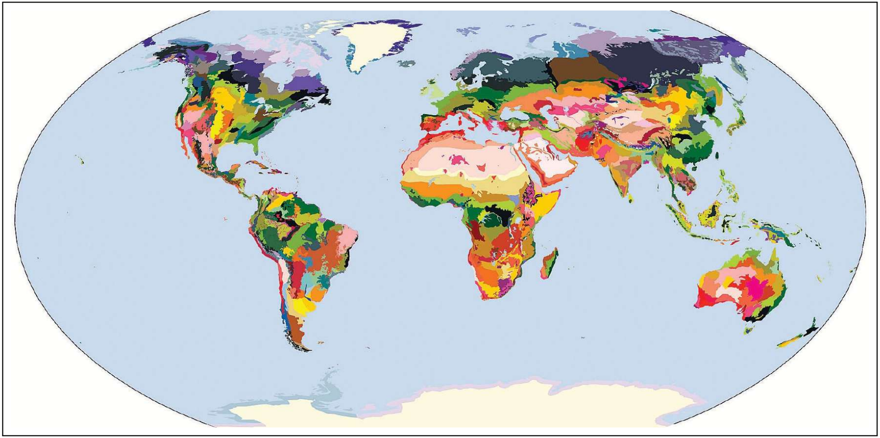
- Terrestrial biomes
  - Boreal forests (taiga)
  - Chaparral (Mediterranean climate)
  - Deserts
  - Savannas
  - Temperate forests
  - Temperate grasslands
  - Tropical rainforests
  - Tundra
- Aquatic biomes
  - Freshwater biomes (wetlands)
  - Marine biomes (oceans, coral reefs and mangroves)

8 realms:

- Australalasia
- Antarctic
- Afrotropic
- Indo-Malaya
- Nearctic
- Neotropic
- Oceania
- Palearctic

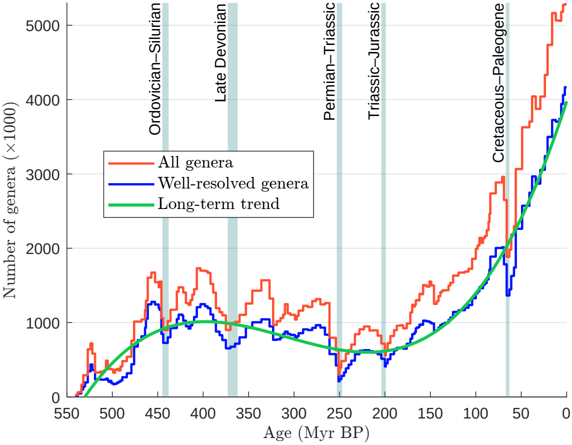
Ecological diversity

Figure 4: The 867 terrestrial ecoregions of Olson *et al.* (2001)



Biodiversity loss (and gain)

Figure 5: Genus diversity during the Phanerozoic era (Sepkoski curve)



Source: Rohde and Muller (2005) & Author's calculations.

Speciation, extinction and the birth-death model

"Like all species, plants, mammals, and birds have been subject to extinction as a fundamental part of evolution. Indeed, only about 2–4% of all the species that have ever lived during the 600 million years of the fossil record still survive today. Looking at the fossil record, it can be said that invertebrate species and mammals have had an average life span of 5–10 and 1–2 million years, respectively." (Mace, 1998).

$\Rightarrow$ An example with donkeys, horses and zebras (their common ancestor lived 2 millions years ago)

Speciation, extinction and the birth-death model

- The number of species $N(t)$ at time $t+1$ can be expressed as:

$$N(t+1) = N(t) + \Delta N^{+}(t+1) - \Delta N^{-}(t+1)$$

where $\Delta N^{+}(t+1)$ and $\Delta N^{-}(t+1)$ are the number of new species and extinct species between t and $t+1$

- In continuous time, this equation becomes:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = \frac{\mathrm{d}N^{+}(t)}{\mathrm{d}t} - \frac{\mathrm{d}N^{-}(t)}{\mathrm{d}t}$$

- Dividing both sides by $N(t)$ gives:

$$\underbrace{\frac{\mathrm{d}N(t)}{N(t)\,\mathrm{d}t}}_{\delta(t)} = \underbrace{\frac{\mathrm{d}N^{+}(t)}{N(t)\,\mathrm{d}t}}_{\lambda(t)} - \underbrace{\frac{\mathrm{d}N^{-}(t)}{N(t)\,\mathrm{d}t}}_{\mu(t)}$$

Speciation, extinction and the birth-death model

- The growth rate $\delta(t)$ is the difference between the origination (or speciation) rate $\lambda(t)$ and the extinction rate $\mu(t)$:

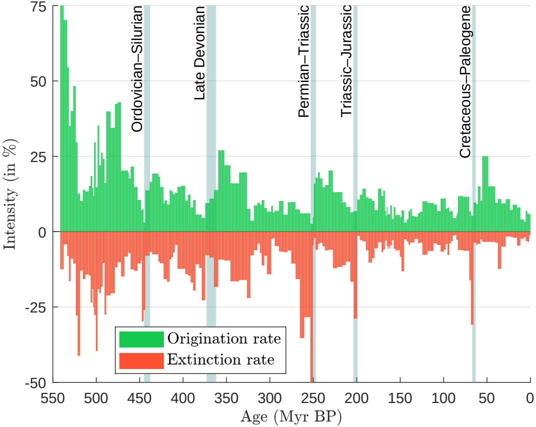
$$\delta(t) = \lambda(t) - \mu(t)$$

- $\delta(t)$ is called the **net diversification rate**
- The average net diversification rate is equal to:

$$\bar{\delta}(t_1, t_2) = \frac{\delta(t_1, t_2)}{t_2 - t_1} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \delta(t) \, \mathrm{d}t$$

Speciation, extinction and the birth-death model

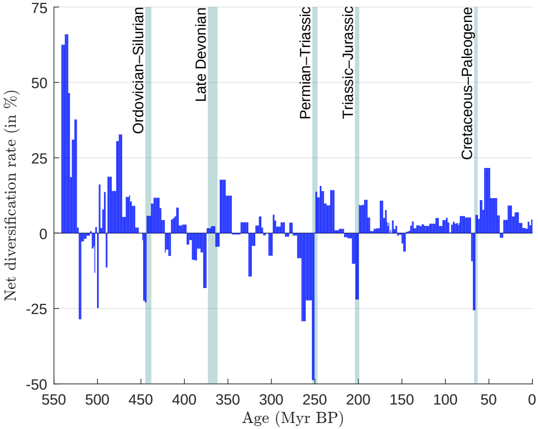
Figure 6: Rates of origination and extinction during the Phanerozoic era



Source: Rohde and Muller (2005) & Author's calculations.

Speciation, extinction and the birth-death model

Figure 7: Net diversification rate during the Phanerozoic era



Source: Rohde and Muller (2005) & Author's calculations.

Calculation of the extinction rate

- If the extinction rate μ equals 0.1% per millennium, we have:

$$\mu = \frac{0.1\%}{1 \text{ millenium}} = \frac{0.1\%}{1000 \text{ years}} = 0.0001\% \text{ per year}$$

- The lifespan (or average lifetime) of species is the inverse of the extinction rate:

$$\tau = \frac{1}{\mu} = \frac{1000 \text{ years}}{0.1\%} = 10^6 \text{ years}$$

- η measures the number of extinctions (E) per million species per year (MSY) or E/MSY. The relationship between η, μ and τ is then:

$$\eta = 10^6 \mu = \frac{10^6}{\tau}$$

- If there are 1 million species, the number of extinctions per year would be one:

$$\eta = \frac{0.1\%}{10^3 \text{ years}} \times 10^6 = \frac{10^6}{10^6 \text{ years}} = 1\,\text{E/MSY}$$

Calculation of the extinction rate

Example #1

We consider three datasets with different species:

Species	N_0	ΔN^+	ΔN^-	Δt
Birds	5 000	7	5	10 years
Insects	75 000	25	50	3 centuries
Plants	10^6	30×10^3	15×10^3	1 millennium

where N_0 is the number of species at the beginning of the period, and ΔN^+ and ΔN^- are the number of new and dead species during the period Δt

Calculation of the extinction rate

Species	λ (in % per year)	μ (in % per year)	δ (in % per year)	λ (in % per millenium)	μ (in % per millenium)	δ (in % per millenium)
Birds	0.01400	0.01000	0.00400	14.00	10.00	4.00
Insects	0.00011	0.00022	−0.00011	0.11	0.22	−0.11
Plants	0.00300	0.00150	0.00150	3.00	1.50	1.50

Species	$\mu(0, \Delta t)$ (in %)	μ (in % per year)	$\mu^\star$ (in % per year)	τ (in years)	$\tau^\star$ (in years)	η (in E/MSY)	$\eta^\star$ (in E/MSY)
Birds	0.10000	0.01000	0.01401	10 000	7 138	100.0	140.1
Insects	0.06667	0.00022	0.00011	450 000	899 850	2.2	1.1
Plants	1.50000	0.00150	0.00305	66 667	32 831	15.0	30.5

*Logarithm calculation: $\mu^\star$, $\tau^\star$ and $\eta^\star$

Background extinction rate

Definition

The background extension rate $\bar{\eta}$ is the normal or typical extension rate that has occurred over the past 500 million years. By normal, we mean the long-term rate at which species would go extinct in the absence of human presence.

$$0.1\,\text{E/MSY} \leq \bar{\eta} \leq 1\,\text{E/MSY}$$

Estimates of the background extension rate $\bar{\eta}$

Taxonomy	τ (in myr)	η (in E/MSY)	Source
All species	1 – 10	0.10 – 1.00	Pimm *et al.* (1995)
All species	1.0	0.10	De Vos *et al.* (2015)
All fossil groups	0.5 – 5	0.20 – 2.00	Simpson (1952)
Marine fossil groups	7.4 – 20	0.05 – 0.13	Raup and Sepkoski (1982)
Marine invertebrates	5 – 10	0.10 – 0.20	Valentine (1970)
Cetacea (genus)	3.61	0.277	Van Valen (1973)
Devonian & Cenozoic bivalves	6.5 – 9.7	0.10 – 0.15	Valentine (1970)
Silurian graptolites	2.0 – 3.0	0.33 – 0.50	Rickards (1977)
Diatoms	8.02	0.125	Van Valen (1973)
Dinoflagellata	13.12	0.076	Van Valen (1973)
Foraminifera (planktonic)	7.21	0.139	Van Valen (1973)
Foraminifera (genus)	24.04	0.042	Van Valen (1973)
Foraminifera (family)	72.13	0.014	Van Valen (1973)
Arthropods	1.07 – 11.11	0.090 – 0.934	De Vos *et al.* (2015)
Chordates	1.71 – 15.63	0.064 – 0.586	De Vos *et al.* (2015)
Mammals	0.56	1.800	Barnosky *et al.* (2011)
Mammals & birds	0.55 – 4.80	0.208 – 1.818	Loehle and Eschenbach (2012)
Mammals	9.80 – 43.48	0.023 – 0.102	De Vos *et al.* (2015)
Mammals	0.50	2.000	Ceballos *et al.* (2015)
Mollusca	0.60 – 7.41	0.135 – 1.672	De Vos *et al.* (2015)
Primates (genus)	3.28	0.305	Van Valen (1973)
Reptilia (family)	24.05	0.042	Van Valen (1973)
Plants	2.84 – 18.87	0.053 – 0.352	De Vos *et al.* (2015)
Plants	7.69 – 20.00	0.050 – 0.130	Gray (2019)

Mass extinction

Definition

- A mass extinction is a widespread and rapid decline in Earth's biodiversity (genetic or species diversity), during which a substantial proportion of the planet's species disappear over a relatively short period of time — typically thousands to millions of years, which is short on the geologic time scale
- The characterization of an extinction event is then determined using calculated extinction rates:

$$[t_1, t_2] \text{ is an extinction period} \Leftrightarrow \mu(t_1, t_2) \geq \mu^{\star} \text{ and } \bar{\eta}(t_1, t_2) \gg \bar{\eta}$$

- Small extinction events
- Pulse events
- '*Big Five*' extinctions

Mass extinction

1. Ordovician-Silurian mass extinction — LOME (445–443 Myr BP)
   About 27% of all families, 57% of all genera and 85% of all species became extinct
2. Late Devonian mass extinction — LDME (372–359 Myr BP)
   About 19% of all families, 35-50% of all genera and 75% of all species became extinct
3. Permian-Triassic extinction or '*The Great Dying*' — EPME (252–251 Myr BP)
   About 57% of marine families, 84% of marine genera, 81% of all marine species and 90% of terrestrial vertebrate species became extinct
4. Triassic-Jurassic extinction — ETME (200–201 Myr BP)
   About 23% of all families, 48% of all genera (20% of marine families and 55% of marine genera) and 70-75% of all species became extinct
5. **Cretaceous-Paleogene extinction** — ECME (66 Myr BP)
   About 17% of all families, 47% of all genera and 75% of all species became extinct

Mass extinction

Holocene extinction, Anthropocene extinction or sixth mass extinction?

IUCN Red List

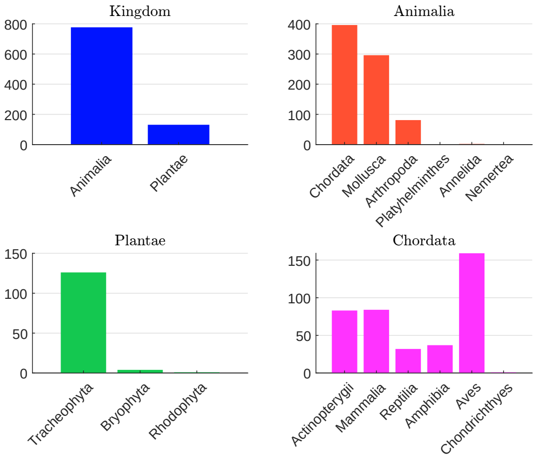
IUCN Red List of Threatened Species

- Not Evaluated (NE) & Data Deficient (DD)
- Least Concern (LC) & Near Threatened (NT)
- Vulnerable (VU), Endangered (EN) & Critically Endangered (CR)
- Extinct in the Wild (EW)
- Extinct (EX)

https://www.iucnredlist.org/search

IUCN Red List

Figure 8: Number of extinct species since 1500 AD



Source: IUCN (2024), `www.iucnredlist.org` & Author's calculations.

IUCN Red List

Table 5: Statistics of the IUCN Red List database

Kingdom	Animalia	Chromistra	Fungi	Plantae	Total
Extinct	777			131	**908**
Extinct in the Wild	36			45	**81**
Critically Endangered	4 067	4	45	5 915	**10 031**
Endangered	6 426	1	105	11 477	18 009
Vulnerable	7 165	1	178	9 937	17 281
Conservation Dependent	18			114	132
Near Threatened	5 149		66	4 203	9 418
Least Concern	51 689		240	33 373	85 302
Data Deficient	15 895	12	160	5 811	21 878
Total	91 222	18	794	71 006	**163 040**

Source: IUCN (2024), `www.iucnredlist.org` & Author's calculations.

IUCN Red List

Table 6: Number of species assessed and number of threatened species by major group of organisms

Taxon	Clade	Number of species	Evaluated species #	Evaluated species %	Threatened species #	Threatened species %
Vertebrates	Mammals	6 701	5 983	89.3%	1 338	22.4%
	Birds	11 195	11 195	100.0%	1 354	12.1%
	Reptiles	12 162	10 309	84.8%	1 844	17.9%
	Amphibians	8 744	8 011	91.6%	2 873	**35.9%**
	Fishes	36 863	27 972	75.9%	3 927	14.0%
	Subtotal	75 665	63 470	83.9%	11 336	17.9%
Plants	Mosses	21 925	327	1.5%	181	**55.4%**
	Ferns and Allies	11 800	821	7.0%	321	39.1%
	Gymnosperms	1 113	1 059	95.1%	451	42.6%
	Flowering Plants	369 000	68 704	18.6%	26 367	38.4%
	Green Algae	13 960	17	0.1%	0	0.0%
	Red Algae	7 523	78	1.0%	9	11.5%
	Subtotal	425 321	71 006	16.7%	27 329	38.5%

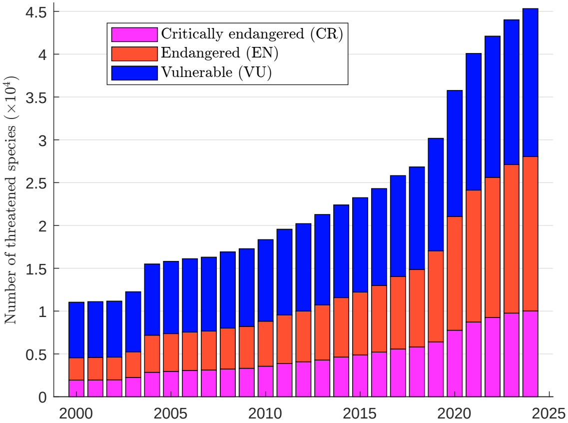
IUCN Red List

Table 7: Number of species assessed and number of threatened species by major group of organisms

Taxon	Clade	Number of species	Evaluated species #	Evaluated species %	Threatened species #	Threatened species %
Invertebrates	Insects	1 053 578	12 718	1.2%	2 415	19.0%
	Molluscs	86 859	9 111	10.5%	2 451	26.9%
	Crustaceans	90 531	3 213	3.5%	747	23.2%
	Corals	5 623	831	14.8%	252	30.3%
	Arachnids	95 894	774	0.8%	272	35.1%
	Velvet Worms	222	11	5.0%	9	**81.8%**
	Horseshoe Crabs	4	4	100.0%	2	50.0%
	Others	157 543	1 090	0.7%	174	16.0%
	Subtotal	1 490 254	27 752	1.9%	6 322	22.8%
Fungi	Mushrooms, etc.	156 313	794	0.5%	328	**41.3%**
	Brown Algae	4 683	18	0.4%	6	33.3%
	Subtotal	160 996	812	0.5%	334	41.1%
	Total	2 152 236	163 040	7.6%	45 321	**27.8%**

IUCN Red List

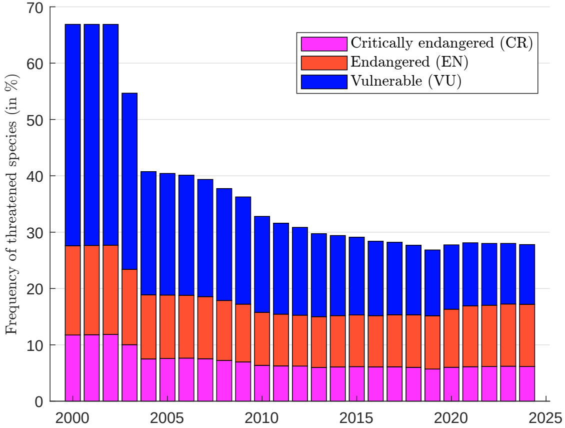
Figure 9: Number of species in the threatened categories (CR, EN, and VU)



Source: IUCN (2024), `www.iucnredlist.org` & Author's calculations.

IUCN Red List

Figure 10: Percentage of species in the threatened categories (CR, EN, and VU)



Source: IUCN (2024), `www.iucnredlist.org` & Author's calculations.

Extinction debt

"The idea that species can initially survive habitat change but later become extinct without any further habitat modification has a long history. It was first conceptualized in island biogeography (MacArthur and Wilson, 1967) and further elaborated by Jared Diamond, who introduced the term relaxation time as the delay of expected extinctions after habitat loss. According to theoretical predictions and supporting empirical data, the relaxation time increases with increasing patch area and with decreasing isolation. A second root stems from metapopulation modeling. Tilman et al. (1994) introduced the term ***extinction debt*** *and considered the order of extinctions in relation to competitive dominance [...] The concept of extinction debt is related to* ***relaxation time*** *but specifies the number or proportion of extant species predicted to become extinct as the species community reaches a new equilibrium after an environmental perturbation." (Kuussaari et al., 2009).*

Extinction debt

- Halley *et al.* (2016) is assumed that the remaining habitat area is reduced from A_0 to A
- The species richness $S(t)$ is given by:

$$\frac{\mathrm{d}S(t)}{\mathrm{d}t} = \lambda(t) - \mu(t) S(t)$$

- The remaining habitat contains a (constant) number $N(t)$ of individuals, which is proportional to the area A and the density ρ of individuals per unit area: $N(t) = \rho A$
- $n(t) = N(t) / S(t)$ is the average population size per species
- At time $t = 0$, we have $n = N_0 / S_0 = \rho A / S_0$ where $S(0) = S_0$ is the initial species richness
- The extinction rate is described by:

$$\mu(t) = kn(t)^{-\alpha} = k \left(\frac{S(t)}{N(t)} \right)^{\alpha}$$

Extinction debt

- We deduce that:

$$\frac{\mathrm{d}S(t)}{\mathrm{d}t} = \lambda(t) - k\left(\frac{S(t)}{\rho A}\right)^{\alpha} S(t) = \lambda(t) - \frac{k}{n^{\alpha} S_0^{\alpha}} S(t)^{\alpha+1}$$

- If we assume that $\lambda(t) = 0$, the solution is:

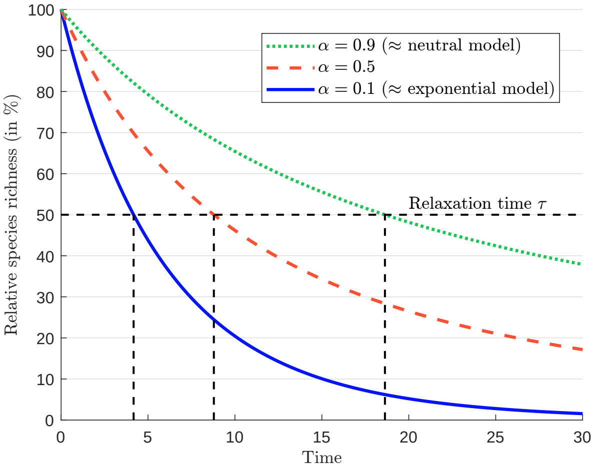
$$S(t) = S_0 \left(1 + \frac{k\alpha}{n^{\alpha}} t\right)^{-1/\alpha}$$

- Extinction debt is quantified by the relaxation time τ, which represents the time required for species richness to decrease by half:

$$S_0 \left(1 + \frac{k\alpha}{n^{\alpha}} \tau\right)^{-1/\alpha} = \frac{S_0}{2} \Leftrightarrow \tau = (2^{\alpha} - 1) \frac{n^{\alpha}}{k\alpha} \propto n^{\alpha}$$

Extinction debt

Figure 11: Relative species richness and relaxation time



Extinction debt

- We assume a constant origination rate: $\lambda(t) = \lambda$
- The equilibrium state $\bar{S}$ is reached when the rate of change in species richness becomes zero:

$$\frac{\mathrm{d}S(t)}{\mathrm{d}t} = 0 \Leftrightarrow \lambda - \frac{k}{n^{\alpha} S_0^{\alpha}} \bar{S}^{\alpha+1} = 0 \Leftrightarrow \bar{S} = \left(\frac{\lambda n^{\alpha} S_0^{\alpha}}{k}\right)^{1/(\alpha+1)}$$

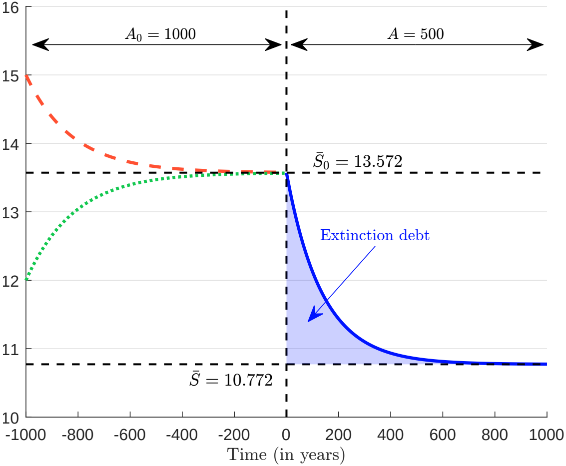
  This is the value of the steady state after the reduction of the area to A
- Before reducing the area, the steady state $\bar{S}_0$ satisfies the following equation:

$$\lambda - \frac{k}{n_0^{\alpha} \bar{S}_0^{\alpha}} \bar{S}_0^{\alpha+1} = 0 \Leftrightarrow \bar{S}_0 = \left(\frac{\lambda (\rho A_0)^{\alpha}}{k}\right)^{1/(\alpha+1)}$$

  because the original habitat area was A_0 and $n_0 = \rho A_0 / \bar{S}_0$

Extinction debt

Figure 12: Extinction debt and steady state



Biodiversity hotspot

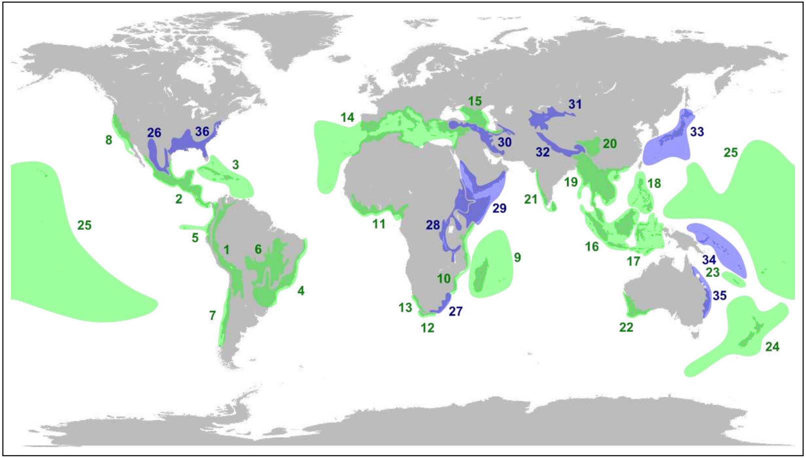
Definition

A biodiversity hotspot is a region of the world that is both rich in plant and animal species and highly threatened by human activities. Specifically, it is characterized by the following two criteria:

- **Exceptional levels of endemism**: The region must have at least 1 500 species of vascular plants that are endemic, meaning that they are found nowhere else on Earth;
- **High levels of habitat loss**: The region must have lost at least 70% of its original natural vegetation, typically due to human activities such as deforestation, agriculture, or urbanization.

Biodiversity hotspot

Figure 13: The 36 biodiversity hotspots



Biodiversity hotspot

The 36 regions are (1) Tropical Andes, (2) Mesoamerica, (3) Caribbean Islands, (4) Atlantic Forest, (5) Tumbes-Chocó-Magdalena, (6) Cerrado, (7) Chilean Winter Rainfall-Valdivian Forests, (8) California Floristic Province, (9) Madagascar and the Indian Ocean Islands, (10) Coastal Forests of Eastern Africa, (11) Guinean Forests of West Africa, (12) Cape Floristic Region, (13) Succulent Karoo, (14) Mediterranean Basin, (15) Caucasus, (16) Sundaland, Indonesia and Nicobar islands of India, (17) Wallacea of Indonesia, (18) Philippines, (19) Indo-Burma, Bangladesh, India and Myanmar, (20) Mountains of Southwest China, (21) Western Ghats and Sri Lanka, (22) Southwest Australia, (23) New Caledonia, (24) New Zealand, (25) Polynesia-Micronesia, (26) Madrean pine-oak woodlands, (27) Maputaland-Pondoland-Albany, (28) Eastern Afromontane, (29) Horn of Africa, (30) Irano-Anatolian, (31) Mountains of Central Asia, (32) Eastern Himalaya, (33) Japan, (34) East Melanesian Islands, (35) Eastern Australian temperate forests, and (36) North American Coastal Plain

Ecosystem functions and services

*"In our increasingly technological society, people give little thought to how dependent they are on the proper functioning of ecosystems and the crucial services for humanity that flow from them. Ecosystem services are "**the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life**"; in other words, "**the set of ecosystem functions that are useful to humans**". Although people have been long aware that natural ecosystems help support human societies, the explicit recognition of "ecosystem services" is relatively recent." (Sekercioglu, 2010).*

Ecosystem functions and services

Sekercioglu (2010) classified ecosystem services into 6 categories:

1. Climate and biogeochemical cycles (climate stability, air purification, UV protection)
2. Regulation of the hydrological cycle (drought mitigation, flood mitigation, water purification)
3. Soils and erosion (detoxification and decomposition of wastes, soil formation and soil fertility)
4. Biodiversity and ecosystem function (ecosystem goods)
5. Mobile linkages (pollination, seed dispersal)
6. Nature's remedies for emerging diseases (medicine, pest control)

$\Rightarrow$ Millennium Ecosystem Assessment, IPBES, ENCORE, TNFD, etc.

Classification of ecosystem functions and services

1. Aesthetic and cultural services

- Aesthetic, symbolic and spiritual values (nature inspires creativity, provides spiritual connections, and contributes to cultural identity)
- Cultural and spiritual significance (many ecosystems have deep cultural, historical or spiritual significance for local communities and indigenous peoples)
- Educational, scientific and research services (biodiversity provides opportunities for scientific study and learning)
- Recreational opportunities and tourism (forests, parks and other natural areas provide opportunities for recreation and tourism)
- Visual amenity services (non-material benefits that contribute to well-being, emotional satisfaction, and cultural enrichment)

Classification of ecosystem functions and services

2. Provisioning services

- Energy (natural processes by which ecosystems produce energy such as biomass, solar energy capture, and fossil fuels)
- Food and feed (agriculture, biomass supply, fisheries, plants, animals, seafood, and livestock)
- Genetic resources (biodiversity provides genetic material essential for breeding crops and livestock, and developing new technologies)
- Medicinal and biochemical resources (many medicines and pharmaceutical products are derived from natural compounds found in biodiversity)
- Raw materials (timber, fuel wood, minerals, fibers, and other natural resources)
- Water supply (clean water for drinking, irrigation, and industrial use)

Classification of ecosystem functions and services

3. Regulating services

- Air quality regulation (ecosystems filter pollutants from the air, improving air quality)
- Climate regulation (forests absorb carbon dioxide and help regulate global temperatures)
- Waste detoxification and decomposition (natural decomposition of organic matter, natural ability to detoxify chemicals and pollutants)
- Erosion control (vegetation helps stabilize soils, reducing erosion and preventing landslides)
- Hazard and extreme event regulation (flood, storm, rainfall)
- Pest and disease control (natural predators and parasites help regulate populations of harmful organisms)
- Pollination and seed dispersal (bees, birds, insects, and other pollinators allow many plants to reproduce)
- Water purification (freshwater, wetlands, & forests filter pollutants)

Classification of ecosystem functions and services

4. Supporting services

- Habitat creation and maintenance (habitats are the natural environments in which organisms live, grow, and reproduce; they form the basis of ecosystems by providing the resources necessary for species to thrive)
- Nutrient cycling (the movement of nutrients through ecosystems, essential for plant growth and productivity)
- Photosynthesis (plants convert solar energy into chemical energy, producing oxygen and forming the base of the food chain)
- Primary production (the production of organic material by plants and algae forms the foundation of ecosystems)
- Soil formation and fertility (the breakdown of rocks and organic matter to create soil)
- Water cycle regulation (ecosystems play an important role in regulating the water cycle, from evaporation to precipitation)

Natural capital

- Ecosystem services are derived from natural capital, which can be defined as the world's stock of natural assets, including geology, soil, air, water, and all living things
- The concept of natural capital in biodiversity is generally attributed to David Pearce

Natural capital

Table 8: Total value of annual ecosystem services in 1997 (1995 price levels)

Biome	Area (in ha $\times 10^6$)	Value (in \$/ha/yr)	Total value (in \$ bn/yr)	Breakdown (in %)
Marine	36 302	577	20 949	63.0
Open ocean	33 200	252	8 381	25.2
Coastal	3 102	4 052	12 568	37.8
Terrestrial	15 323	804	12 319	37.0
Forest	4 855	969	4 706	14.1
Grassland & meadow	3 898	232	906	2.7
Wetland	330	14 785	4 879	14.7
Lake & river	200	8 498	1 700	5.1
Desert	1 925			
Tundra	743			
Ice & rock	1 640			
Cropland	1 400	92	128	0.4
Urban	332			
Total	51 625		**33 268**	100.0

Source: Costanza *et al.* (1997) & Author's calculations.

Natural capital

According to the World Economic Forum (2020) **$44 trillion of economic value creation** — more than half of global GDP — **is moderately or highly dependent on nature**

The three largest industries most dependent on nature are:

1. Construction ($4 tn)
2. Agriculture ($2.5 tn)
3. Food and beverages ($1.4 tn)

Pollination service

There are two main types of pollination:

1. Self-pollination
2. Cross-pollination

We also distinguish three methods of cross-pollination:

1. **Abiotic pollination** involves natural transport phenomena such as wind, water, and rain
2. **Biotic pollination** requires living pollinators to move pollen from one flower to another
3. **Hand pollination** (also known as mechanical or human pollination) is a technique in which humans manually transfer pollen from the male to the female plant

The story of the original vanilla bean

The Chinantla Forest is considered the birthplace of vanilla, and the vanilla plant, or vine, is native to Mexico. There, the vines grew and flourished without the help of humans. Wild vanilla is naturally pollinated by melipona bees and small hummingbirds found only in Mexico. Before 1850, all vanilla beans came from the forests of Mexico, and France was the number one importer of the '*black flower*'. The Aztecs, and the Mayans before them, believed that the scent of vanilla could help them communicate with the gods and had long mastered the fermentation techniques needed to cure the beans. They cultivated '*tlilxotchitl*' or black flowers so that the flavors could be combined with cocoa and coffee. In 1521, Cortés was the first European to bring the dark pods or beans back to Charles Quint. Vanilla beans first arrived in France in 1664. Later, Louis XIV fell in love with the taste of vanilla and wanted vanilla beans to be grown on the island of Réunion, then known as Bourbon Island. But until the mid-19th century, vanilla beans were still only made in Mexico. Although the technique of curing the beans was known, pollination of the flower was not. In 1836 and 1841, Charles Morren, a Belgian botanist, and Edmond Albius, a slave on Réunion Island discovered how to bypass bee pollination by manually pollinating vanilla flowers. Soon after, vanilla plants were exported by the French to plantations in Tahiti, Madagascar, Mauritius, Réunion Island, and the Comoros.

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Pollination service

- Klein *et al.* (2007) identified 124 major crops, representing 99% of total world food production

Pollination	Dependent	Independent	Not evaluated	Total
Number of crops	87	28	9	124
(in %)	**70%**	**23%**	7%	100%
Production (2024)	**35%**	**60%**	5%	100%

- Aizen *et al.* estimated that the direct reduction in total agricultural production in the absence of animal pollination would be 5% for developed regions and 8% for developing regions

Why?

Pollination service

Table 9: How dependent are foods on pollinator insects?

	No dependency: yields are not affected by pollinators
	Cereals: barley, maize, millet, oats, rice, rye, sorghum, wheat
	Roots and tubers: carrots, cassava, potatoes, sweet potatoes
	Legumes including chickpeas, lentils, peas
	Fruit and veg including bananas, grapes, lettuce, pepper, pineapples
	Sugar crops: sugar beet, sugar cane
	Also includes areca nuts, asparagus, broccoli, cabbages, castor oil seed, cauliflower, chicory roots, dates, garlic, hazelnuts, jojoba seeds, leeks, olives, onions, pistachios, quinoa, spinach, taro, triticale, walnuts, yams

Source: Klein *et al* (2007) & Aizen *et al.* (2019).

Pollination service

Table 10: How dependent are foods on pollinator insects?

	Little dependency: yield reduction of 0% to 10% without pollinators
	Fruits and veg including lemons, limes, oranges, papayas, tomatoes
	Oilcrops including linseed, palm oil, poppy seed, safflower seed
	Legumes including beans (dry & green), cow peas, pigeon peas
	Groundnuts
	Also includes bambara beans, chillies, clementines, grapefruit, mandarins, persimmons, string beans, tangerines

Source: Klein *et al* (2007) & Aizen *et al.* (2019).

Pollination service

Table 11: How dependent are foods on pollinator insects?

Modest dependency: yield reduction of 10% to 40% without pollinators
Oilcrops including mustard seed, rapeseed, sesame, sunflower seed
Soybeans
Fruits including currants, egglant, figs, gooseberries, strawberries
Coconuts and okra
Coffee beans
Also includes broad beans, chestnut, karite nuts, seed cotton

Source: Klein *et al* (2007) & Aizen *et al.* (2019).

Pollination service

Table 12: How dependent are foods on pollinator insects?

High dependency: Yield reduction of 40% to 90% without pollinators	
	Fruits including apples, apricots, blueberries, cherries, cranberries, guavas, mangoes, nectarines, peaches, plums, pears, raspberries
	Nuts including almonds, cashew nuts, kola nuts
	Avocados
	Also includes anise, badian, buckwheat, coriander, cucumber, fennel, nutmeg

Source: Klein *et al* (2007) & Aizen *et al.* (2019).

Pollination service

Table 13: How dependent are foods on pollinator insects?

	Essential: yield reduction greater than 90% without pollinators
	Fruits including kiwi, melons, pumpkins, watermelons
	Cocoa beans
	Brazil nuts
	Also includes quinces, vanilla

Source: Klein *et al* (2007) & Aizen *et al.* (2019).

Pollination service

- Let $V_{j,t}^{(\mathrm{nutritional})}$ be the total amount of nutrient j in year t

$$V_{j,t}^{(\mathrm{nutritional})} = \sum_{i=1}^{n} V_{i,j}^{(\mathrm{nutritional})} P_{i,t} \left(1 - R_i\right)$$

where $V_{i,j}^{(\mathrm{nutritional})}$ is the amount of nutrient j in a metric tonne of crop i, $P_{i,t}$ is the volume production in tonnes of crop i in year t, and R_i is the proportion of crop i that is not consumed by humans due to inedible parts, such as pits, stems, or shells

- $V_{j,t}^{(1)} = \sum_{i=1}^{n} \mathbb{1}\left\{\delta_i = 0\right\} \cdot V_{i,j}^{(\mathrm{nutritional})} P_{i,t} \left(1 - R_i\right)$ is **the nutritional value of pollinator-independent crops**
- $V_{j,t}^{(2)} = \sum_{i=1}^{n} \mathbb{1}\left\{\delta_i > 0\right\} \cdot \left(1 - \delta_i\right) V_{i,j}^{(\mathrm{nutritional})} P_{i,t} \left(1 - R_i\right)$ is **the nutritional value of pollinator-dependent crops due to abiotic and self-pollination**
- $V_{j,t}^{(3)} = \sum_{i=1}^{n} \mathbb{1}\left\{\delta_i > 0\right\} \cdot \delta_i V_{i,j}^{(\mathrm{nutritional})} P_{i,t} \left(1 - R_i\right)$ is **the nutritional value of pollinator-dependent crops attributed to animal pollination alone**

Pollination service

Table 14: Proportion in % of nutrients derived from pollinator-independent and pollinator-dependent crops

Nutrient		$V_{j,t}^{(1)}$	$V_{j,t}^{(2)}$	$V_{j,t}^{(3)}$
Macro-nutrients	Energy	78.83	18.59	2.58
	Protein	83.43	13.57	3.00
	Fat	26.02	66.98	7.00

Source: Eilers *et al.* (2011).

Pollination service

Table 15: Proportion in % of nutrients derived from pollinator-independent and pollinator-dependent crops

Nutrient		$V_{j,t}^{(1)}$	$V_{j,t}^{(2)}$	$V_{j,t}^{(3)}$
Vitamins	A	28.71	30.26	**41.03**
	β-carotene	27.44	34.19	**38.37**
	α-carotene	32.25	29.83	**37.92**
	E (α-tocopherol)	63.73	28.94	7.33
	E (β-tocopherol)	0.63	72.50	**26.87**
	E (γ-tocopherol)	32.92	52.66	14.42
	K	71.55	19.28	9.17
	C	6.99	73.37	19.64
	B1 (Thiamin)	95.29	4.00	0.71
	B2 (Riboflavin)	97.66	1.92	0.42
	B3 (Niacin)	89.46	8.93	1.61

Source: Eilers *et al.* (2011).

Pollination service

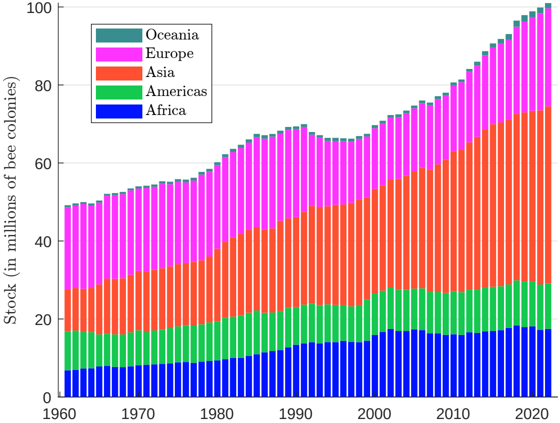
Table 16: Proportion in % of nutrients derived from pollinator-independent and pollinator-dependent crops

Nutrient		$V_{j,t}^{(1)}$	$V_{j,t}^{(2)}$	$V_{j,t}^{(3)}$
	Calcium	42.40	48.49	9.11
	Iron	70.66	23.14	6.20
	Magnesium	88.50	9.06	2.44
	Phosphorus	89.06	8.72	2.22
	Potassium	72.74	20.93	6.33
Minerals	Sodium	87.18	8.63	4.19
	Zinc	91.80	6.54	1.66
	Copper	80.92	15.21	3.87
	Mangan	93.87	4.94	1.19
	Selenium	97.46	1.97	0.57
	Fluoride	45.57	34.60	**19.83**

Source: Eilers *et al.* (2011).

Pollination service

Figure 14: Trend in the number of bee colonies (1961–2022)



Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

Pollination service

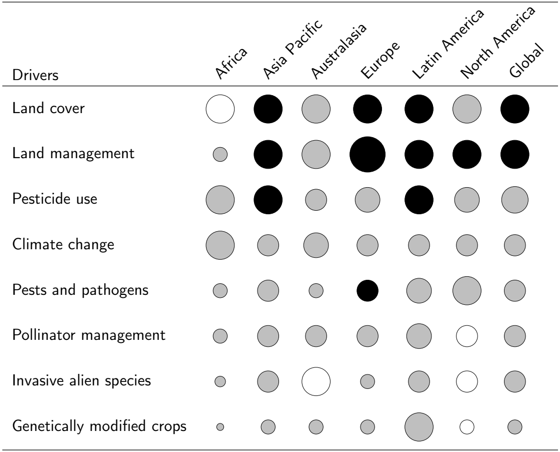
Table 17: Regional distribution of managed honey bee colonies (in millions)

Region	Stock (in million colonies)				Growth (in %)	
	1961	1980	2000	2022	1961–2022	2000–2022
Europe	21.10	21.42	15.55	25.12	19.1	61.6
Western Europe	3.76	3.35	2.45	3.55	−5.5	45.3
Northern Europe	0.44	0.40	0.27	0.64	45.6	138.3
Eastern Europe	14.02	13.71	7.36	10.66	−24.0	44.8
Southern Europe	2.87	3.95	5.47	10.27	257.3	87.6
Americas	10.02	10.03	10.62	11.71	16.9	10.2
Northern America	5.85	4.75	3.22	3.40	−41.9	5.5
Central America	2.26	2.80	2.19	2.68	18.5	22.3
Caribbean	0.23	0.32	0.28	0.40	72.5	45.8
South America	1.67	2.16	4.94	5.23	212.4	6.0
Africa	6.85	9.37	15.92	17.46	155.1	9.7
Asia	10.70	18.61	26.82	45.34	323.6	69.1
Oceania	0.51	0.76	0.80	1.36	168.7	70.9
World	49.17	60.20	69.71	101.00	105.4	44.9

Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

Pollination service

Table 18: Assessment of the importance of the top eight drivers of pollinator decline (Dicks *et al.*, 2021)



Food and feed service

- Production perspective
- Consumption perspective

Food and feed service

Table 19: World production of primary crops

Crop	Production (in billion tonnes)					1961 breakdown		2022 breakdown		Yield (in t/ha)	
	1961	1980	2000	2020	2022	(in %)	(% cum.)	(in %)	(% cum.)	1961	2022
Primary crops	2.54	4.02	6.14	9.38	9.61	100.00		100.00		2.61	6.49
Cereals	0.88	1.55	2.06	3.00	3.06	34.58		31.84		1.35	4.18
Fruit	0.22	0.40	0.68	1.07	1.10	8.87		11.44		7.62	14.09
Oil crops	0.07	0.15	0.32	0.66	0.68	2.90		7.06		0.33	1.01
Pulses, Roots and Tubers	0.50	0.56	0.75	0.96	1.00	19.56		10.44		4.45	6.02
Sugar crops	0.61	1.00	1.50	2.13	2.18	24.02		22.73		38.16	71.61
Vegetables	0.20	0.29	0.69	1.15	1.17	7.79		12.21		9.34	20.13
Other	0.06	0.06	0.15	0.41	0.41	2.28		4.29			

Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

Food and feed service

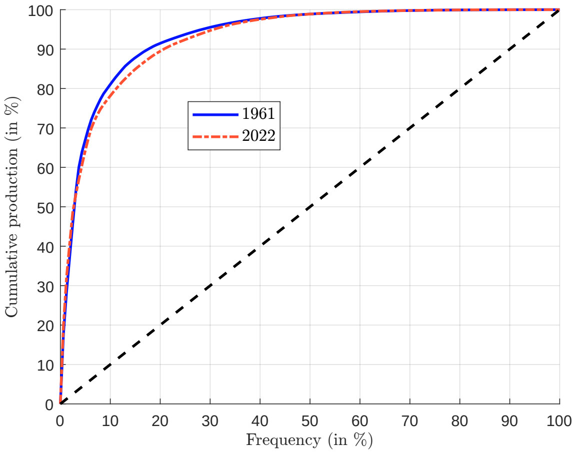
Table 20: World production of primary crops

Crop	Production (in billion tonnes)					1961 breakdown		2022 breakdown		Yield (in t/ha)	
	1961	1980	2000	2020	2022	(in %)	(% cum.)	(in %)	(% cum.)	1961	2022
Sugar cane	0.45	0.73	1.25	1.88	1.92	17.66	17.66	20.00	20.00	50.27	73.67
Maize (corn)	0.21	0.40	0.59	1.16	1.16	8.09	25.75	12.11	32.11	1.94	5.72
Wheat	0.22	0.44	0.59	0.76	0.81	8.77	34.52	8.41	40.52	1.09	3.69
Rice	0.22	0.40	0.60	0.77	0.78	8.50	43.02	8.08	48.60	1.87	4.70
Oil palm fruit	0.01	0.03	0.12	0.42	0.42	0.54	43.56	4.42	53.02	3.77	14.15
Potatoes	0.27	0.24	0.32	0.37	0.37	10.67	54.23	3.90	56.92	12.22	21.07
Soya beans	0.03	0.08	0.16	0.36	0.35	1.06	55.29	3.63	60.55	1.13	2.61
Cassava, fresh	0.07	0.12	0.18	0.31	0.33	2.81	58.10	3.44	63.99	7.40	10.31
Other vegetables	0.06	0.09	0.21	0.29	0.30	2.46	60.55	3.10	67.09	8.42	14.53
Sugar beet	0.16	0.27	0.25	0.25	0.26	6.33	66.88	2.72	69.81	23.17	60.77
Tomatoes	0.03	0.05	0.11	0.19	0.19	1.09	67.97	1.94	71.74	16.43	37.84
Barley	0.07	0.16	0.13	0.16	0.15	2.86	70.83	1.61	73.36	1.33	3.29
Bananas	0.02	0.04	0.07	0.13	0.14	0.88	71.71	1.41	74.76	10.65	22.75
Onions and shallots	0.01	0.02	0.05	0.11	0.11	0.55	72.26	1.15	75.91	11.68	18.54
Watermelons	0.02	0.03	0.08	0.10	0.10	0.70	72.96	1.04	76.95	9.13	34.27
Apples	0.02	0.03	0.06	0.09	0.10	0.67	73.64	1.00	77.95	9.91	19.86
Cucumbers and gherkins	0.01	0.01	0.04	0.09	0.09	0.38	74.01	0.99	78.94	9.43	43.56
Yams	0.01	0.01	0.04	0.08	0.09	0.33	74.34	0.92	79.85	7.23	8.49
Rape or colza seed	0.00	0.01	0.04	0.07	0.09	0.14	74.48	0.91	80.76	0.57	2.18
Sweet potatoes	0.10	0.14	0.14	0.09	0.09	3.87	78.36	0.90	81.66	7.35	11.92

Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

Food and feed service

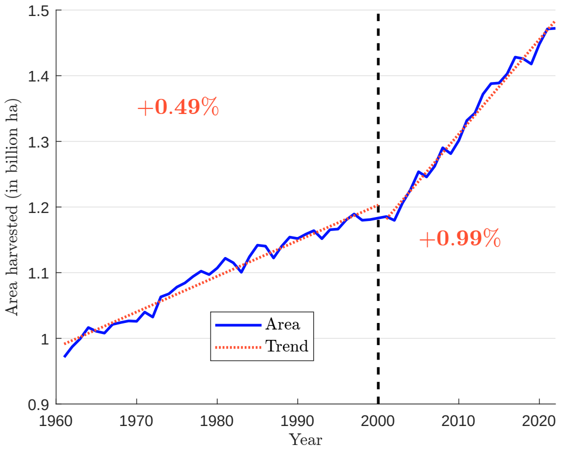
Figure 15: Lorenz curve of world crop production



Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

Food and feed service

Figure 16: Harvested area for crop production



Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

Food and feed service

Table 21: World production of primary livestock (in million tonnes)

Livestock	1961	1970	1980	1990	2000	2010	2020	2021	2022	Growth
Eggs	15	20	27	37	55	69	93	93	93	517%
Milk	344	392	466	542	579	725	921	941	930	170%
Meat	71	101	137	180	232	294	339	355	361	405%
Beef & Buffalo	29	40	47	55	58	67	74	75	76	165%
Pork	25	36	53	70	89	108	108	121	123	395%
Poultry	9	15	26	41	69	99	135	136	139	**1 456%**
Sheep & Goat	6	7	7	10	11	14	16	16	17	176%
Other	3	3	4	4	4	6	6	6	6	106%

Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

Food and feed service

Table 22: Agricultural use of inputs (fertilizers and pesticides)

Input	1961	1980	2000	2020	2022	1961	1980	2000	2020	2022
	Agricultural use (in million tonnes)					Use par area of cropland (in kg/ha)				
Fertilizer	31.0	116.6	135.2	201.7	185.4	20.8	76.8	85.9	123.5	113.1
Nitrogen	11.5	60.6	81.0	114.7	108.1	7.6	39.6	51.3	69.6	65.4
Phosphate	10.9	31.8	32.5	47.8	41.9	7.5	21.4	21.0	29.8	26.0
Potash	8.6	24.2	21.7	39.3	35.5	5.7	15.8	13.7	24.1	21.7
Pesticide			2.2	3.4	3.7			1.5	2.2	2.4

Source: `www.fao.org/faostat/en/#data/RFN`, `www.fao.org/faostat/en/#data/RP` & Author's calculations.

Food and feed service

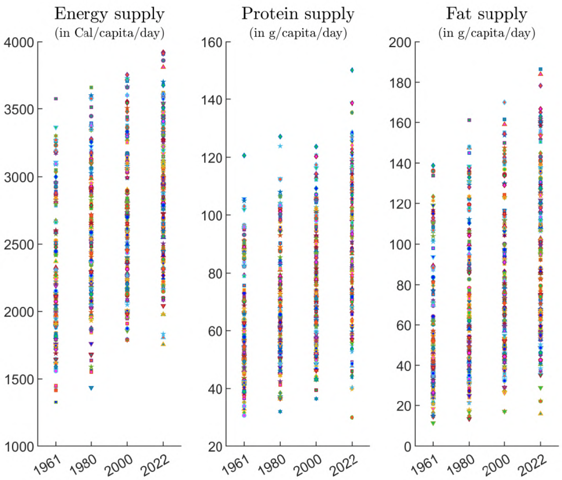
Table 23: Food supply per capital per day (energy, protein & fat)

Region	Energy (in Cal/capita/day)			Protein (in g/capita/day)			Fat (in g/capita/day)		
	1961	1990	2022	1961	1990	2022	1961	1990	2022
Africa	1 993	2 291	2 567	53	59	66	40	47	56
Eastern Africa	1 989	1 925	**2 263**	56	50	**59**	29	32	**47**
Southern Africa	2 603	2 755	2 713	70	73	79	58	64	91
Americas	2 559	2 953	3 392	77	82	104	78	97	135
Northern America	2 873	3 447	**3 881**	95	107	122	110	138	**177**
Caribbean	1 992	2 390	2 828	47	57	75	42	65	78
Asia	1 805	2 414	2 944	47	61	93	25	49	78
South-eastern Asia	1 836	2 178	2 880	40	48	80	27	41	69
Western Asia	2 501	3 273	3 128	76	93	93	57	84	101
Europe	3 041	3 367	3 471	90	104	112	89	125	140
Eastern Europe	3 100	3 360	3 375	95	105	109	73	108	121
Northern Europe	3 176	3 214	3 402	91	96	113	131	134	141
Oceania	3 021	3 139	3 101	100	105	101	108	126	128
Australasia	3 060	3 188	3 417	103	109	**115**	111	129	152
Melanesia	2 534	2 547	2 314	54	65	66	60	86	66
World	2 196	2 621	2 985	61	70	92	48	67	87

Source: `www.fao.org/faostat/en/#data/FBS` & Author's calculations.

Food and feed service

Figure 17: Country dispersion of food supply



Food and feed service

Table 24: Split of food supply between vegetal and animal products

Food Origin	1961 Energy	1961 Protein	1961 Fat	2022 Energy	2022 Protein	2022 Fat
Vegetal	1 858	41.80	22.80	2 460	53.45	51.33
Animal	338	19.66	24.72	525	38.08	35.98
Total	2 196	61.46	47.52	2 945	91.52	87.31

Source: `www.fao.org/faostat/en/#data/FBS`, `www.fao.org/faostat/en/#data/FBSH` & Author's calculations.

Food and feed service

- Irish potato famine (1845–1852)
- Coffee leaf rust outbreak in Sri Lanka (1860–1890)
- Panama disease in bananas (1950s)
- Southern corn leaf blight in the United States (1970)
- Wheat stem rust Ug99 in Africa (1998–present)
- Citrus greening disease in Florida (2005–present)

Food and feed service

Table 25: Share of world crop production exported (in %)

Crop	1961	2021	Crop	1961	2021
Apples	9.4	8.8	**Olive oil**	14.9	66.2
Apricots	5.0	8.6	Onions and shallots	2.0	9.1
Avocados	0.2	36.3	Oranges	16.3	10.0
Bananas	16.6	19.3	Peaches and nectarines	6.0	7.0
Barley	9.9	30.0	Peas	4.0	48.7
Blueberries	36.9	39.7	Persimmons	0.4	14.0
Cauliflowers	6.4	6.1	Pineapples	2.8	12.7
Cherries	2.9	35.2	Pomelos	10.3	11.0
Coconut oil	21.1	80.6	Potatoes	1.0	3.8
Cranberries	0.0	50.9	**Quinoa**	0.0	68.8
Cucumbers	1.5	3.5	Sesame seeds	11.0	32.2
Dates	14.0	19.1	**Soybeans**	15.5	43.2
Eggplants	0.2	1.1	Spinach	0.3	1.1
Kiwi fruit	0.0	36.4	Strawberries	5.4	11.1
Lentils	6.5	67.5	Tomatoes	3.9	4.4
Maize	6.8	16.2	**Vanilla**	73.8	91.6
Mustard seeds	19.3	53.8	Watermelons	0.9	4.7
Natural honey	11.0	42.3	Wheat	17.8	25.9

Source: `www.fao.org/faostat/en/#data/TCL` & Author's calculations.

Food and feed service

Table 26: Share of world crop production exported (in %)

Commodity	1990	2023	Commodity	1990	2023
Beef meat	9.2	18.2	Pork meat	1.9	8.7
Butter	10.0	7.8	Poultry meat	8.5	11.2
Cheese	4.0	13.6	Pulses	10.5	19.8
Cotton	24.2	36.5	Rice	3.4	10.1
Edible fish meals	44.7	67.6	Roots and tubers	7.3	7.8
Eggs	2.6	1.6	Sheep meat	12.2	9.0
Fish	15.4	23.0	Skim milk powder	26.4	57.9
Fresh dairy products	0.0	0.1	Soybeans	26.6	45.1
Maize	12.8	15.3	Sugar	9.8	36.8
Oilseed meals	24.2	24.5	Vegetable oils	24.3	37.2
Other coarse grains	7.7	14.0	Wheat	19.4	24.1
Other oilseeds	15.2	13.6	Whole milk powder	45.9	49.9

Source: `https://data-explorer.oecd.org` & Author's calculations.

The case of maize

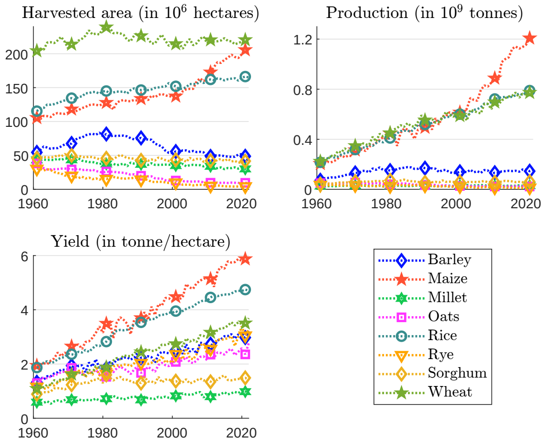
Table 27: Breakdown of maize use

Year	Animal feed	Human food	Losses	Seed	Processing	Other uses
2010	**55.3%**	13.6%	3.5%	0.7%	5.7%	21.2%
2022	**60.4%**	11.4%	5.2%	0.7%	5.8%	16.5%

Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

The case of maize

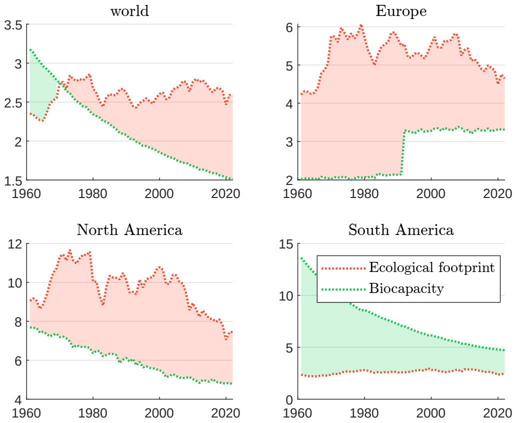
Figure 18: Area harvested, production and yield of cereal crops



Source: `www.fao.org/faostat/en/#data/QCL` & Author's calculations.

Ecological footprint

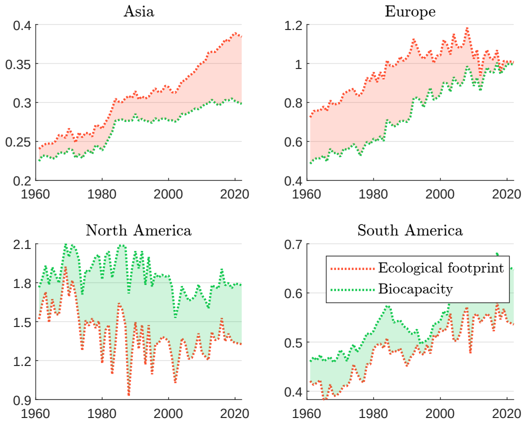
Figure 19: Global ecological footprint and biocapacity (in global hectares per capita)



Source: `https://data.footprintnetwork.org` & Author's calculations.

Ecological footprint

Figure 20: Cropland ecological footprint and biocapacity (in global hectares per capita)



Source: `https://data.footprintnetwork.org` & Author's calculations.

Food security

- Let X and R be the random variables for energy intake and energy requirement, respectively, with a joint probability distribution $\mathbf{F}(x, r)$
- The prevalence of undernourishment is equal to:

$$\mathrm{PoU} = \Pr\{X < R\} = \iint \mathbb{1}\{x < r\} \cdot \mathrm{d}\mathbf{F}(x, r) = \iint_{x<r} f(x, r)\,\mathrm{d}x\,\mathrm{d}r$$

  where $f(x, r)$ is the bivariate density function of (X, R)
- The non-parametric estimator of PoU is the empirical frequency:

$$\mathrm{PoU} = \frac{1}{n}\sum_{i=1}^{n} \mathbb{1}\{x_i < r_i\}$$

  where n denotes the population size and (x_i, r_i) are the observed intake and requirement values for individual i
- Another approach assumes a parametric density function $f(x, r; \theta)$, estimates the vector of parameters θ, and calculates $\mathrm{PoU} = \iint_{x<r} f\left(x, r; \hat{\theta}\right)\,\mathrm{d}x\,\mathrm{d}r$

Food security

- The FAO approximates the prevalence of undernourishment as follows:

$$\mathrm{PoU} = \Pr\left\{X < r_L\right\} = \int_{x<r_L} f_x\left(x\right)\,\mathrm{d}x = \mathbf{F}_x\left(r_L\right)$$

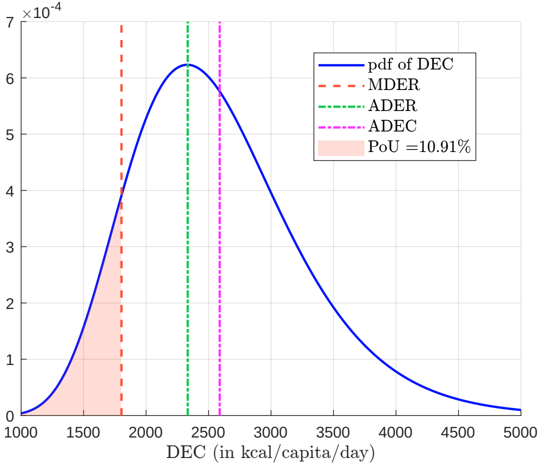
  where:
  - $\mathbf{F}_x\left(x\right)$ is the cumulative distribution function of energy intake, often called dietary energy consumption (DEC)
  - r_L is a cut-off point representing the minimum requirement, also known as the minimum dietary energy requirement (MDER)

- Assuming $X \sim \mathcal{LN}\left(\mu_x, \sigma_x^2\right)$, we get:

$$\left\{\begin{array}{l} \mu_x = \ln \mu\left(X\right) - \dfrac{1}{2}\ln\left(\mathrm{CV}^2\left(X\right)+1\right) \\ \sigma_x = \sqrt{\ln\left(\mathrm{CV}^2\left(X\right)+1\right)} \end{array}\right.$$

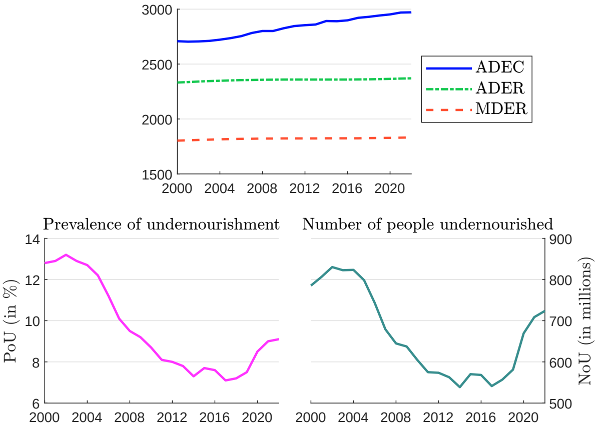
Food security

Figure 21: Dietary energy consumption and prevalence of undernourishment (India, 2022)



Food security

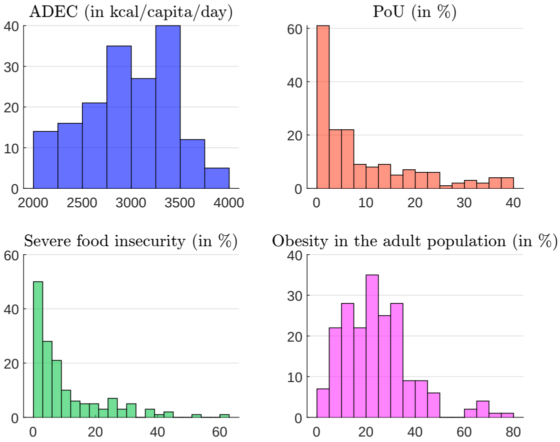
Figure 22: Prevalence of undernourishment and number of undernourished people (World)



Source: `www.fao.org/faostat/en/#data/FS` & Author's calculations.

Food security

Figure 23: Histogram of food insecurity indicators (country level, 2022)



Source: `www.fao.org/faostat/en/#data/FS` & Author's calculations.

Food security

Table 28: Food security indicators by region (2022)

Indicator	Africa	Asia	Europe	North America	Oceania	South America	World
MDER (kcal/capita/day)	1 736	1 831.0	1 931	1 962	1 871	1 856	**1 832**
ADER (kcal/capita/day)	2 237	2 369.0	2 505	2 554	2 424	2 403	2 370
ADEC (kcal/capita/day)	2 578	2 917.0	3 467	3 882	3 104	3 104	**2 971**
Prevalence of undernourishment	19.9	8.2			7.1	6.6	**9.1**
People undernourished (million)	284.1	386.5			3.2	43.9	723.8

All statistics are expressed in %, except those whose units are indicated.

Source: `www.fao.org/faostat/en/#data/FS` & Author's calculations.

Food security

Table 29: Food security indicators by region (2022)

Indicator	Africa	Asia	Europe	North America	Oceania	South America	World
Severe food insecurity							
Total population	21.7	9.7	1.8	0.9	9.3	11.0	**10.8**
Rural adult population	23.5	10.4	1.7	0.8	2.8	13.5	12.2
Town adult population	22.2	10.9	1.9	0.7	4.0	12.9	11.5
Urban adult population	19.8	8.3	1.8	1.2	3.0	9.6	9.3
Male adult population	20.8	8.6	1.7	0.7	8.5	9.6	9.1
Female adult population	21.3	9.9	1.9	1.2	8.3	12.0	10.2
Total population (million)	309.0	459.2	13.3	3.5	4.2	72.5	**861.7**
Male adults (million)	87.9	157.2	6.4	1.0	1.5	23.7	277.7
Female adults (million)	92.0	177.6	7.8	1.9	1.4	31.2	311.9

All statistics are expressed in %, except those whose units are indicated.

Source: `www.fao.org/faostat/en/#data/FS` & Author's calculations.

Food security

Table 30: Food security indicators by region (2022)

Indicator	Africa	Asia	Europe	North America	Oceania	South America	World
Water services							
Safely managed drinking water	33.0	76.0	93.0	97.0		75.0	73.0
Basic drinking water	66.0	95.0	98.0	100.0		98.0	91.0
Sanitation services							
Safely managed sanitation	26.0	59.0	79.0	96.0	73.0	49.0	57.0
Basic sanitation	36.0	86.0	97.0	100.0	80.0	90.0	81.0

All statistics are expressed in %, except those whose units are indicated.

Source: www.fao.org/faostat/en/#data/FS & Author's calculations.

Food security

Table 31: Food security indicators by region (2022)

Indicator	Africa	Asia	Europe	North America	Oceania	South America	World
Children under 5 years							
Affected by wasting	5.8	9.3		0.2		1.4	6.8
Who are stunted	30.0	22.3	4.0	3.6	22.0	11.5	22.3
Who are overweight	4.9	5.1	7.3	8.2	16.8	8.6	5.6
Affected by wasting (million)	12.2	31.6				0.7	45.0
Who are stunted (million)	63.1	76.6	1.4	0.7	0.8	5.7	148.1
Who are overweight (million)	10.2	17.7	2.6	1.7	0.6	4.2	37.0
Obesity							
Adult population	16.2	10.4	21.4	40.3	29.5	29.9	15.8
Adult population (million)	123.9	353.9	129.0	119.2	9.6	141.4	880.7

All statistics are expressed in %, except those whose units are indicated.

Source: `www.fao.org/faostat/en/#data/FS` & Author's calculations.

Biodiversity risks

Measurement

Governance and regulation

The avoid-minimize-restore approach

The impact investing approach