Earth-Space sustainability

Intertwined impacts and vulnerabilities

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Agenda

1. **Anthropocene: the human epoch**
   Societal development and environmental degradation dynamics in a finite world
2. **Ecological overshoot**
   An insight into the vital signs of planet Earth
3. **Transformation pathways**
   Towards a good life for all within planetary boundaries?
4. **Root causes of our inadequate responses**
   Cultural, political and economic brakes to transformational change
5. **Challenges along the way**
   Global systemic risks on the road to net zero
6. **Will we continue space activities?**
   The future of the space sector in the Anthropocene
   - 6.1 **The environmental impacts of space activities**
     - **Game: Space Tchornobyl**
     - **Game: Systems thinking**
   - 6.2 **What space activities in the Anthropocene?**

1.

ANTHROPOCENE: THE HUMAN EPOCH

Societal development and environmental degradation dynamics in a finite world

You are here

1.0
0.8
0.6
0.4
0.2
0.0

energy scale

fossil fuels

?

muscle and firewood

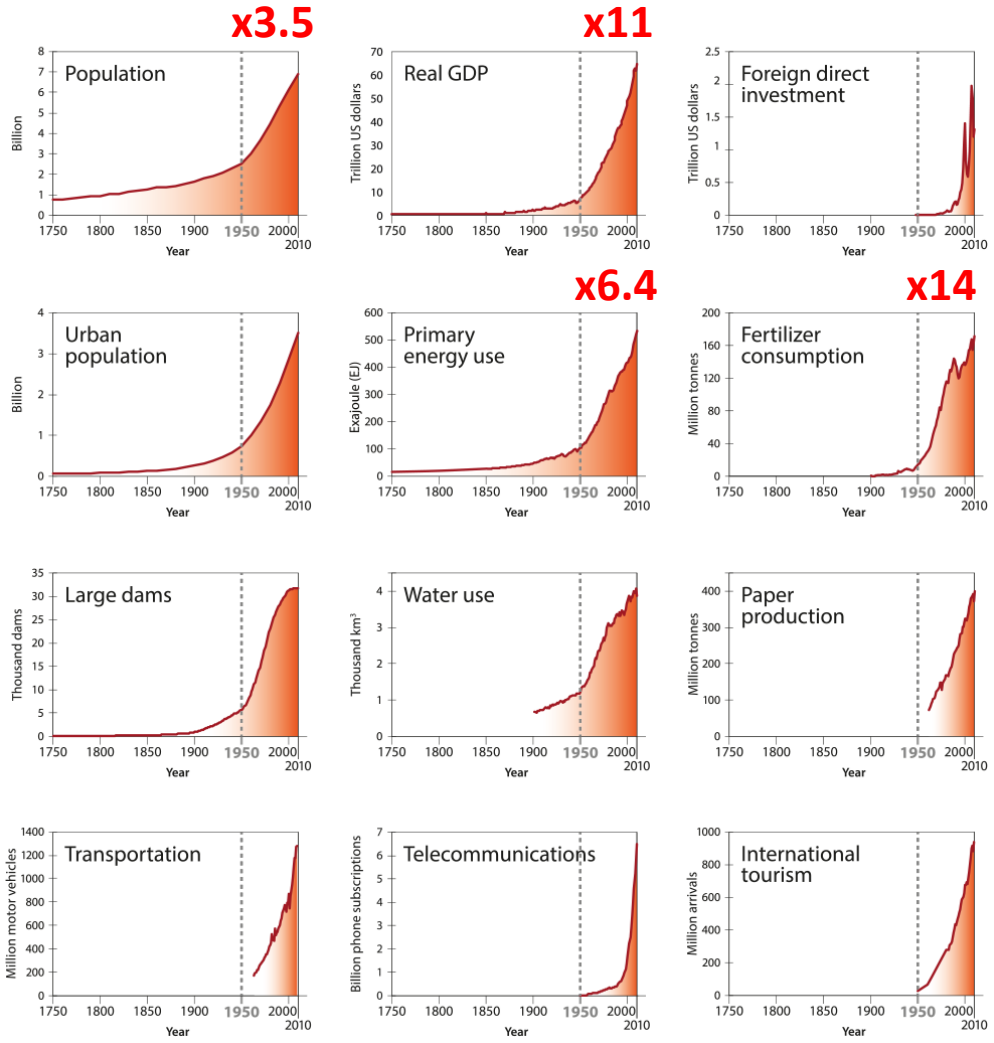
Time

Source: Vaclav Smil, Tom Murphy

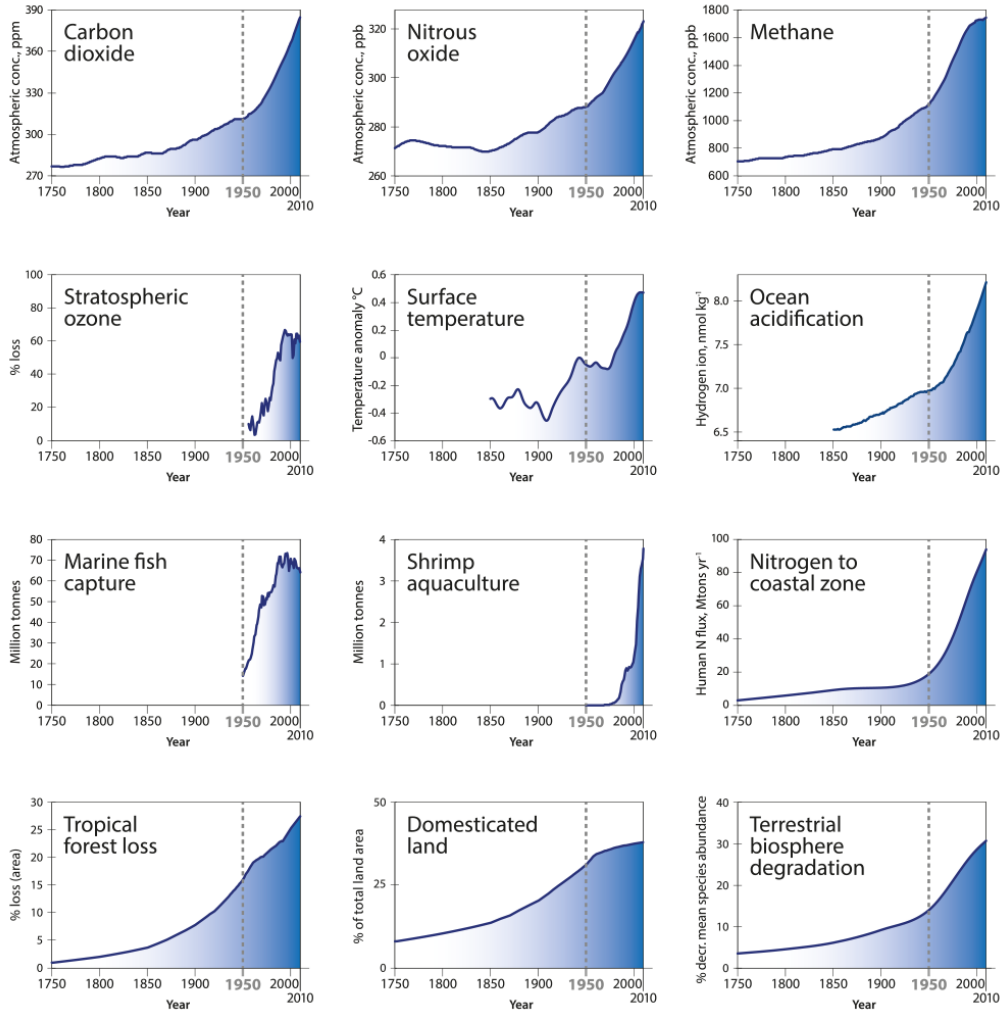
But socio-economic progress was made at a cost

1950-2020 evolution

Socio-economic trends

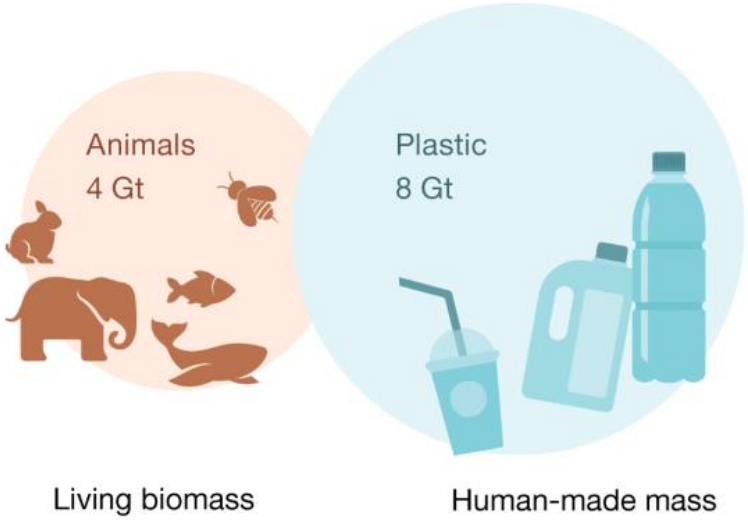


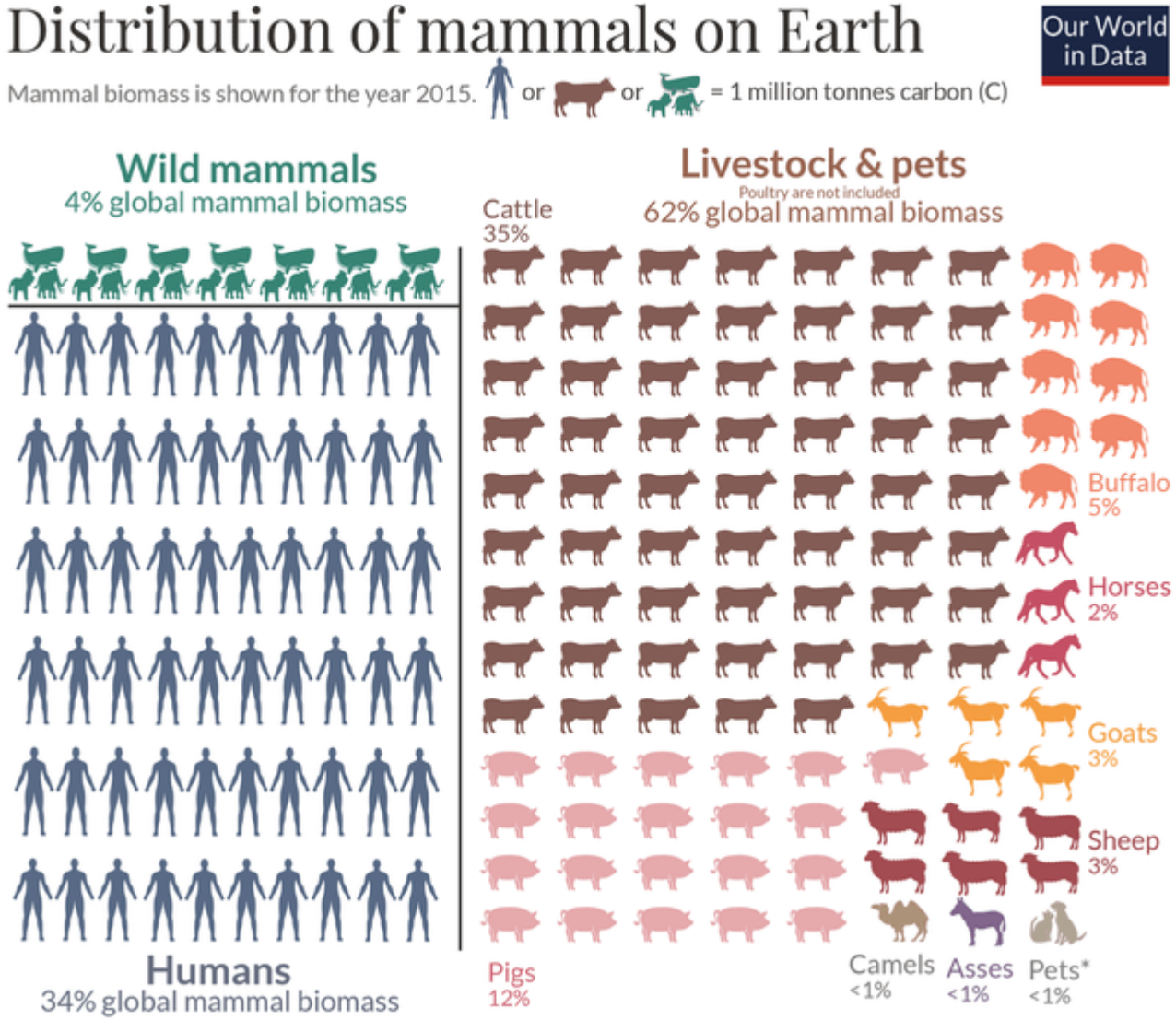
Earth system trends



Steffen et al., 2015 “The trajectory of the Anthropocene: The Great Acceleration”

The scale of human creations on Earth





Source: Elhacham et al. (2020), Greenspoon et al. (2023), OWID

1. Anthropocene: the human epoch

Key takeaways

- Socio-economic progress is very recent and has been made in parallel with a degradation of the Earth's ecosystems and resources
- Humans have become a major driving force in Earth's geology and ecosystems changes
- This occurred using energy exogenous of human's bodies, largely based on fossil fuels
- Human societies are like a giant superorganism consuming natural resources and producing waste
- The ecological footprint of human societies have exceeded Earth's biocapacity

So…

How severe is it?

2.

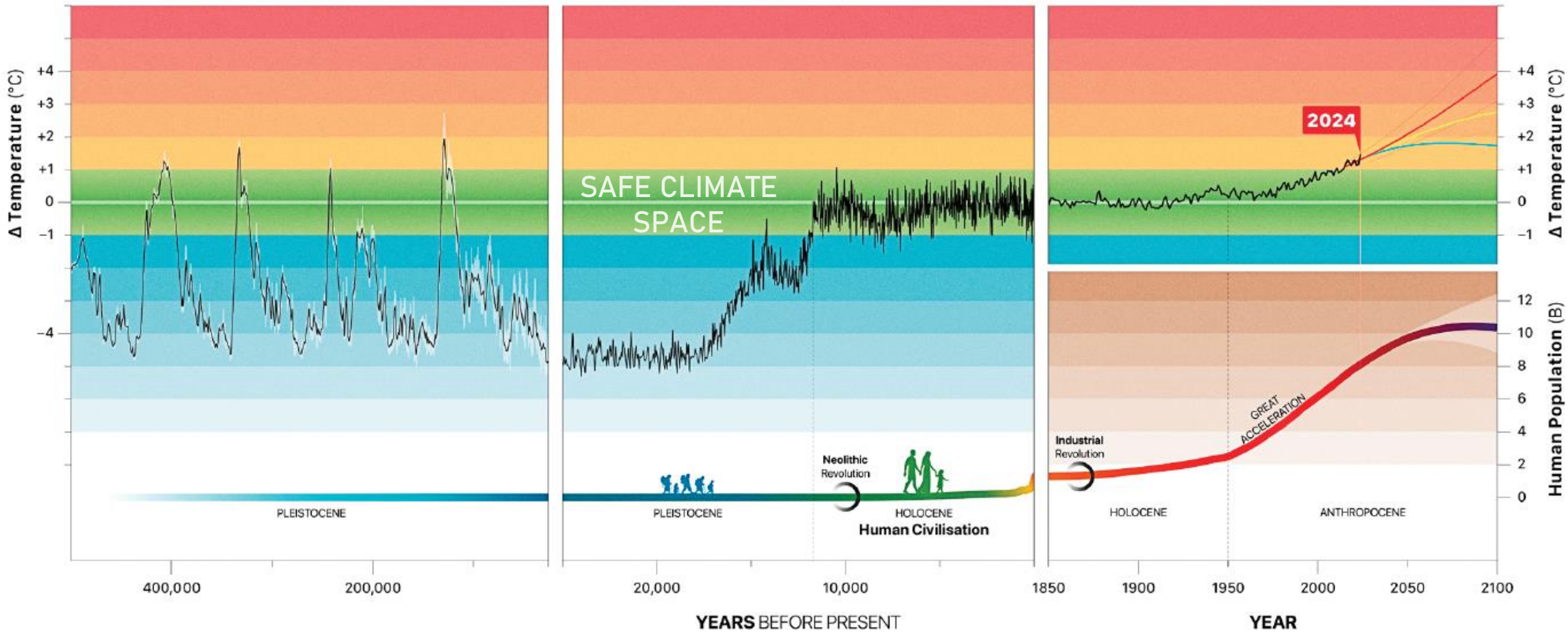
ECOLOGICAL OVERSHOOT

An insight into the vital signs of planet Earth

“I am here to sound the alarm: The world must wake up. We are on the edge of an abyss — and moving in the wrong direction.”
Antonio Guterres, UN Secretery-General

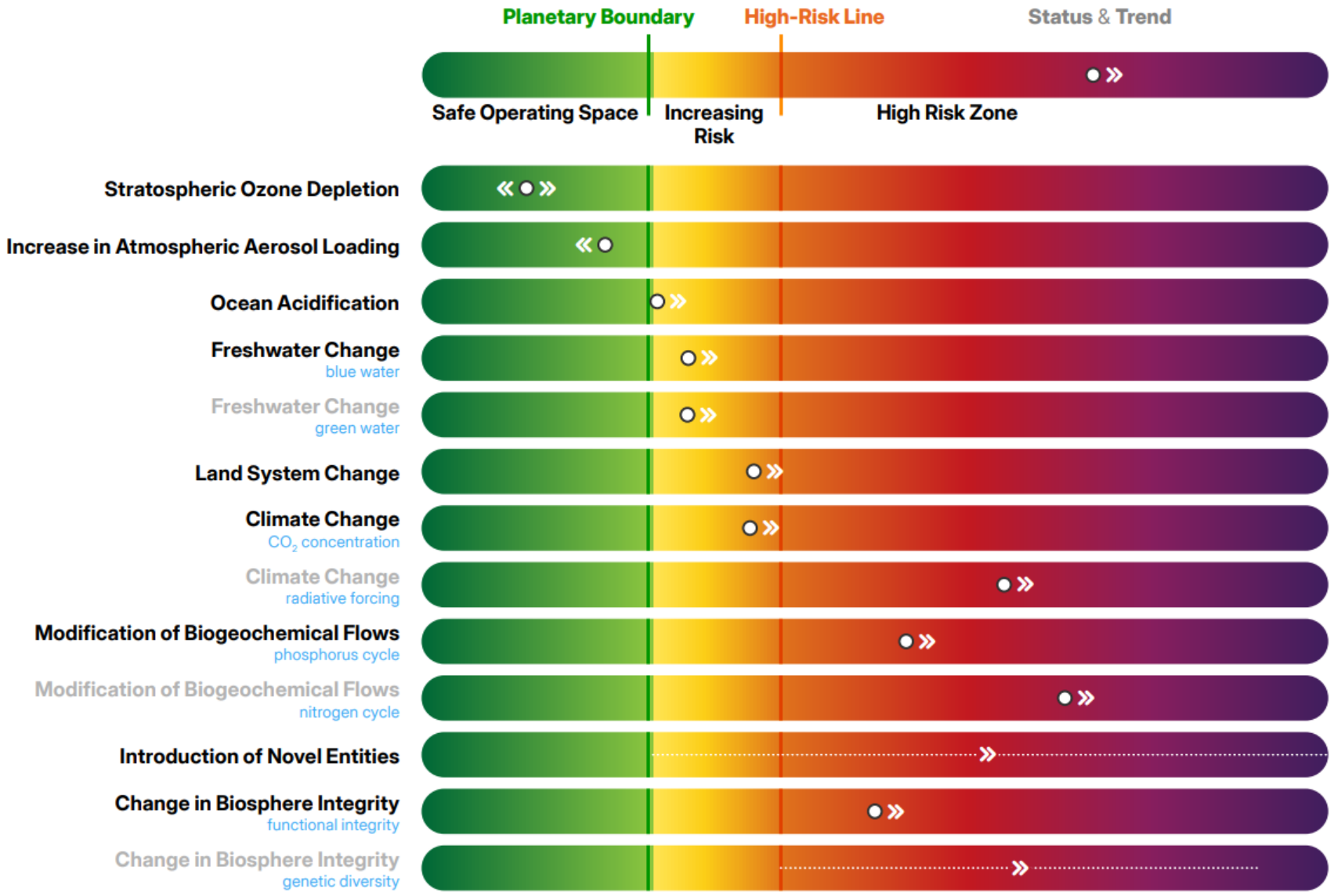
Humanity's Journey on Earth

Human Population Size and Global Temperature from 500,000 Years BP Until 2100



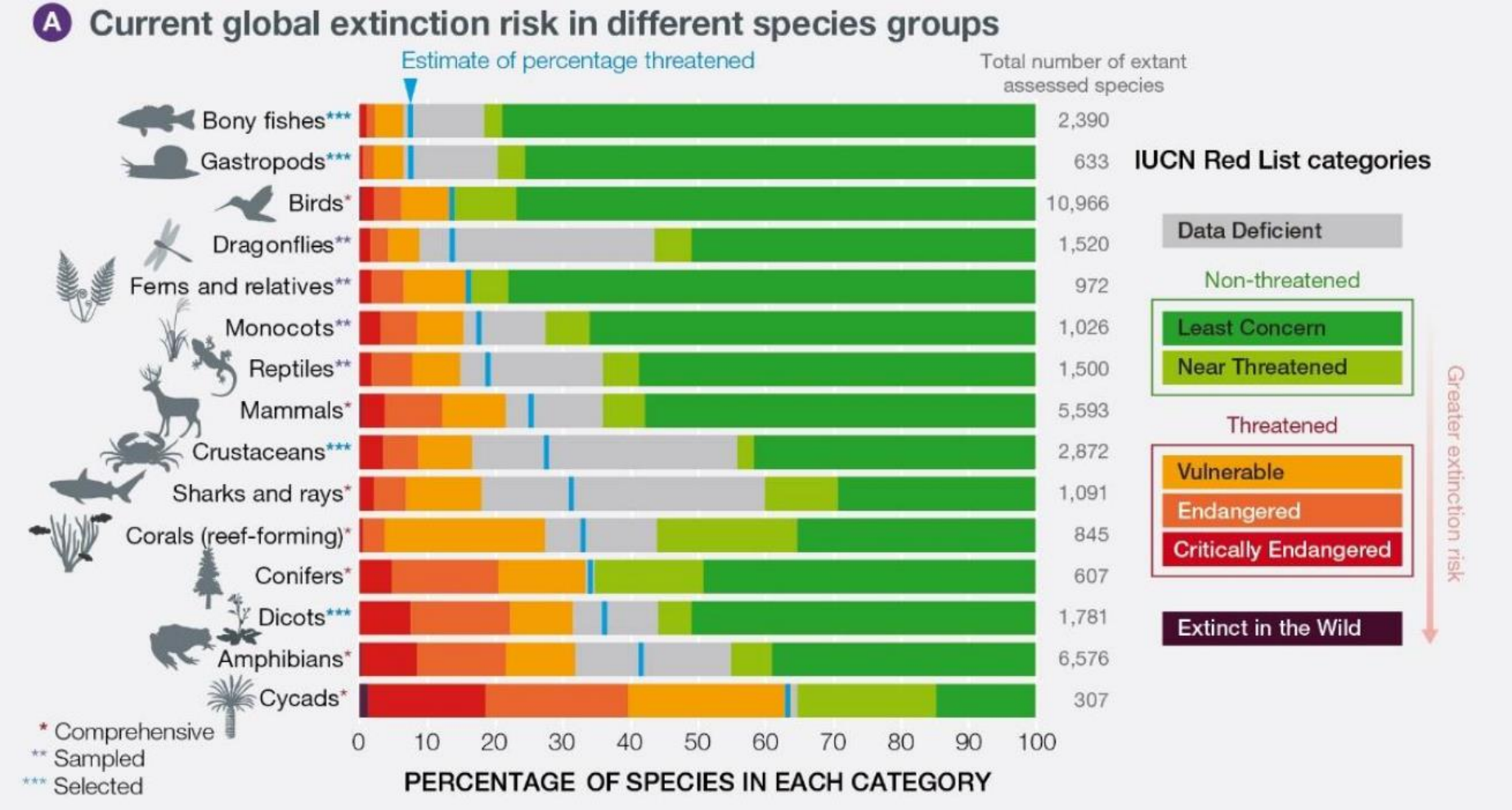
Source: Planetary Health Check

Planetary boundaries… 7 of 9 have been breached



Source: Planetary Health Check 2025

A 6th mass extinction has started



Rate of species extinction is 100-1000x the background rate

"These estimates reveal an exceptionally rapid loss of biodiversity over the last few centuries**, indicating that a sixth mass extinction is already under way"**

RESEARCH ARTICLE | BIOLOGICAL SCIENCES

Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines

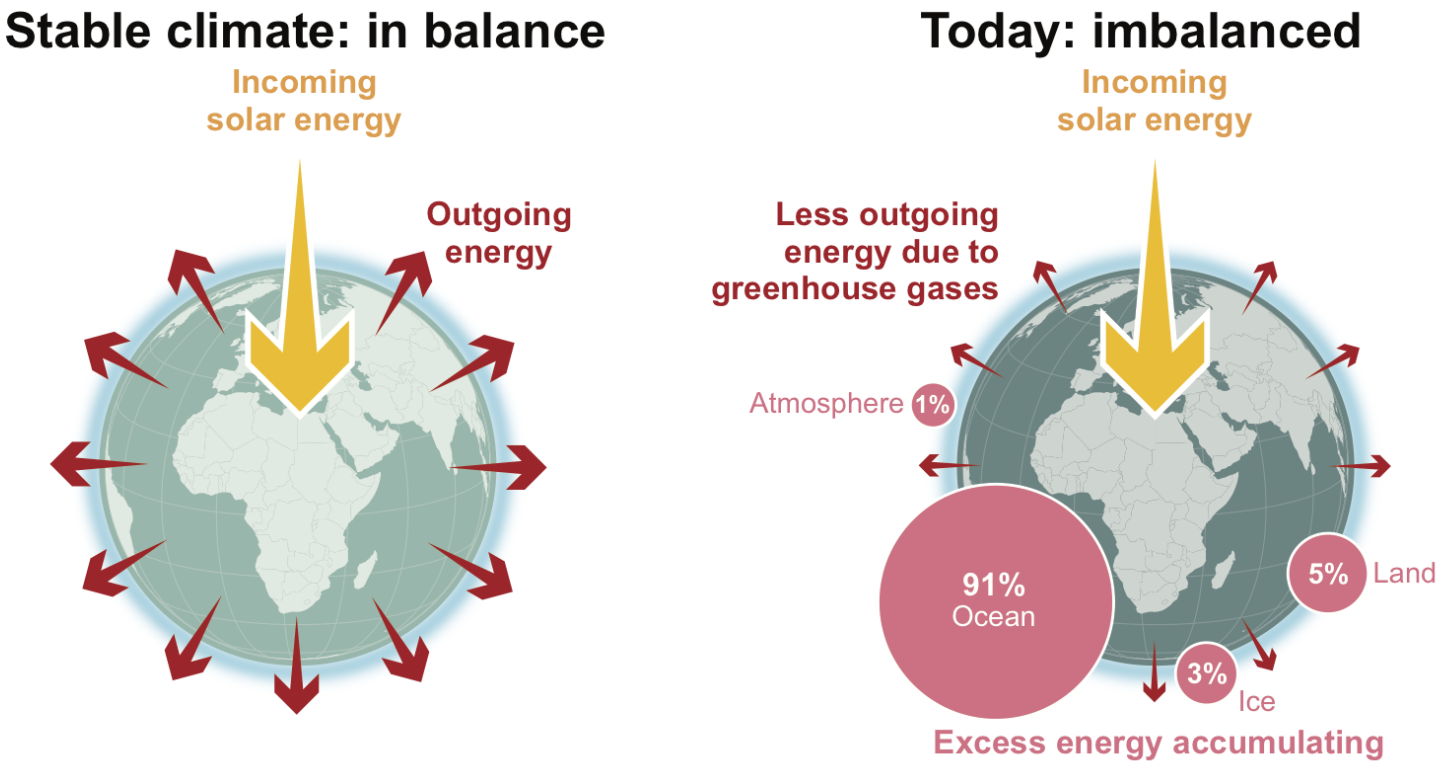
PNAS

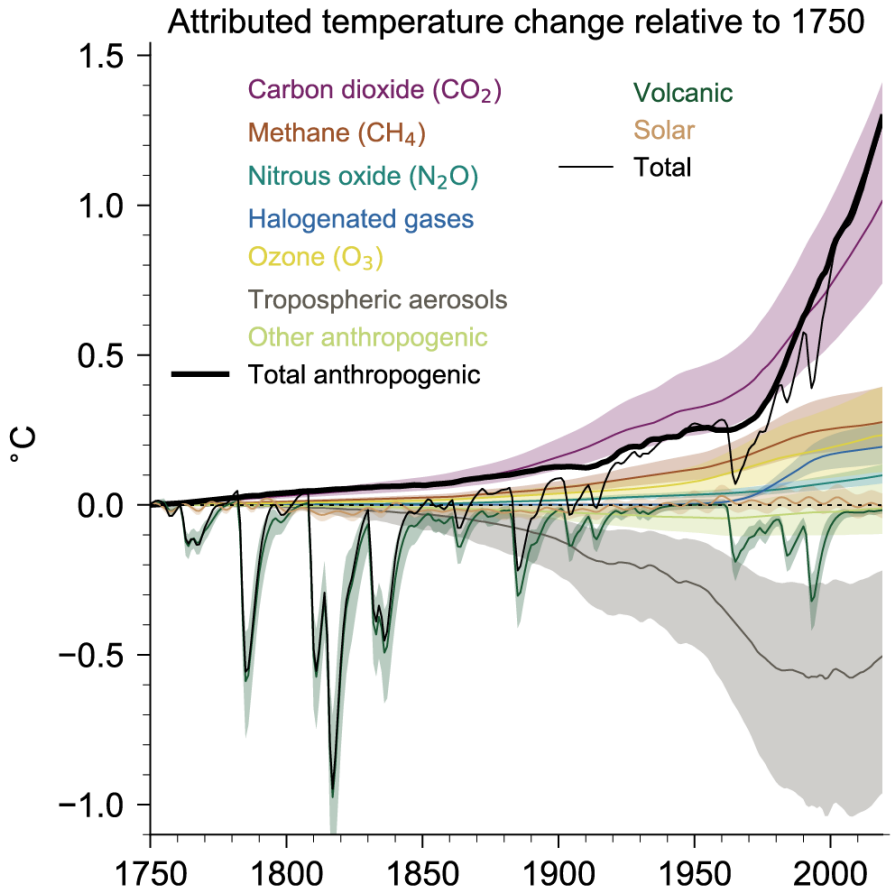
ScienceAdvances

Accelerated modern human–induced species losses: Entering the sixth mass extinction

Sources: IPBES, Pimm et al (2014), Ceballos et al. (2015, 2017)

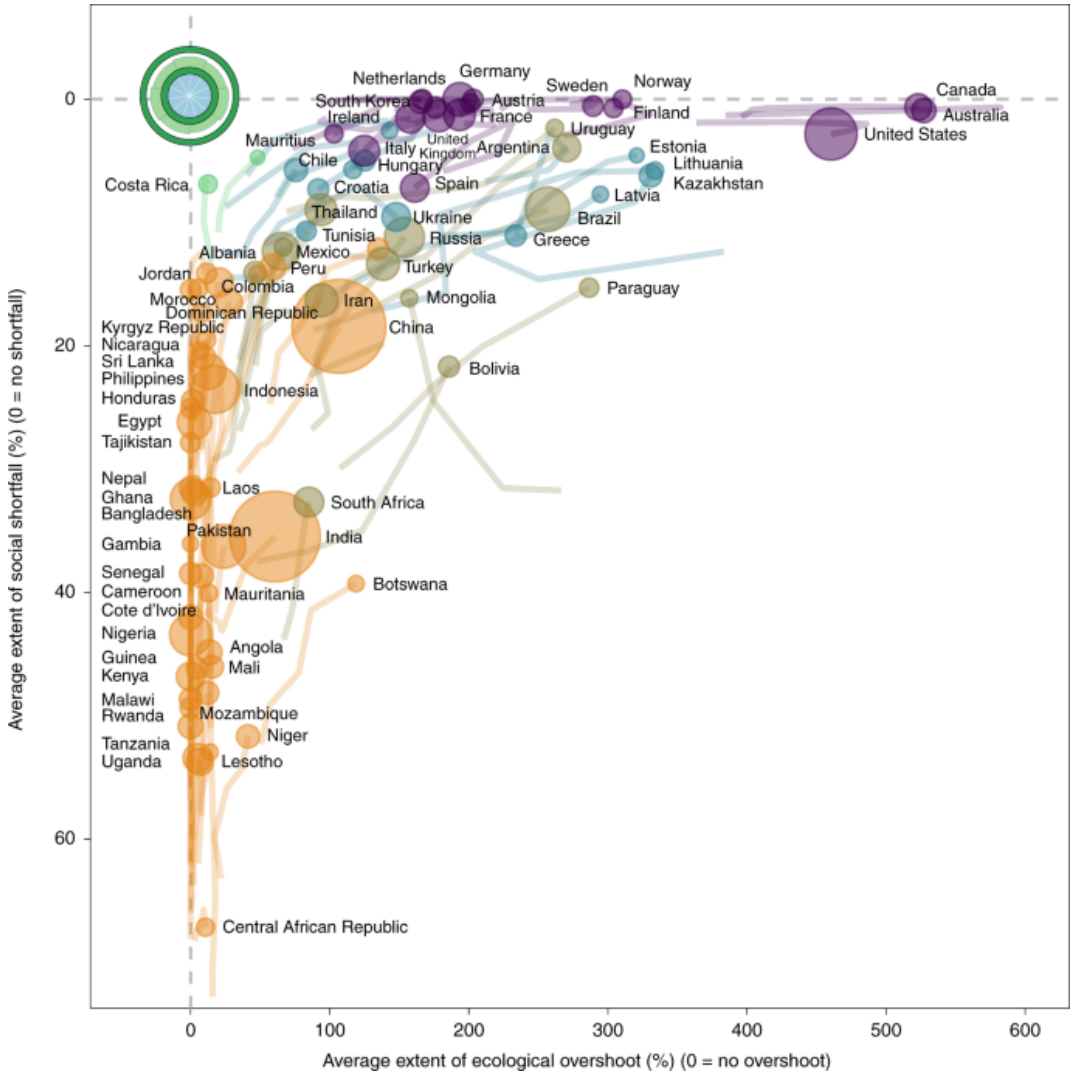
Mechanism of warming and its contributors





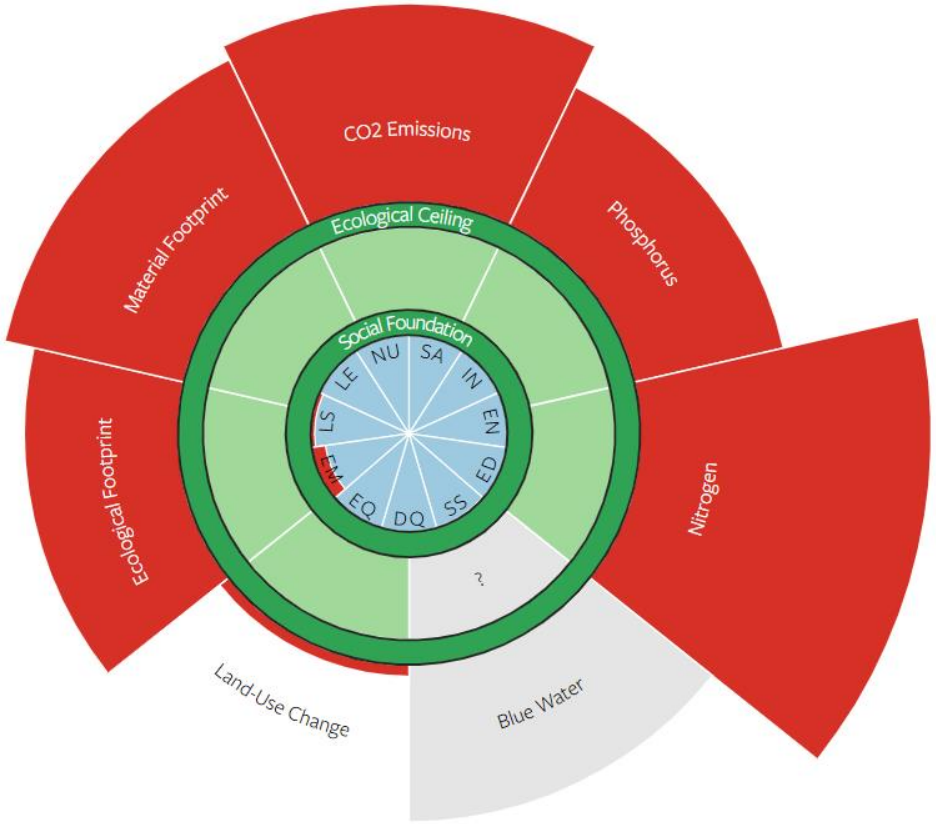
Source: IPCC AR6

The social shortfall and ecological overshoot of nations



Source: Fanning et al. (2022), O'Neill et al (2018)

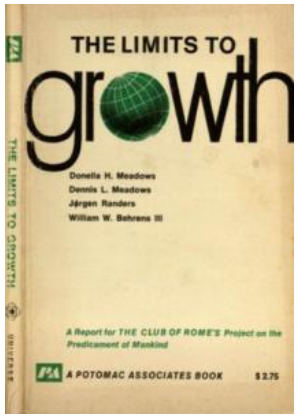
France



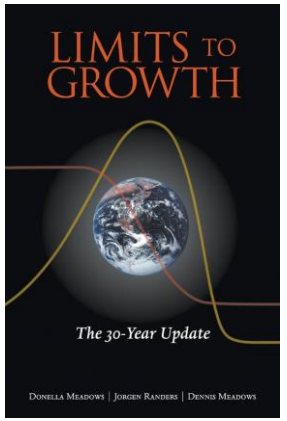
LS - Life Satisfaction	LE - Life Expectancy	NU - Nutrition	SA - Sanitation
IN - Income Poverty	EN - Access to Energy	ED - Education	SS - Social Support
DQ - Democratic Quality	EQ - Equality	EM - Employment	

"Doughnut economics"

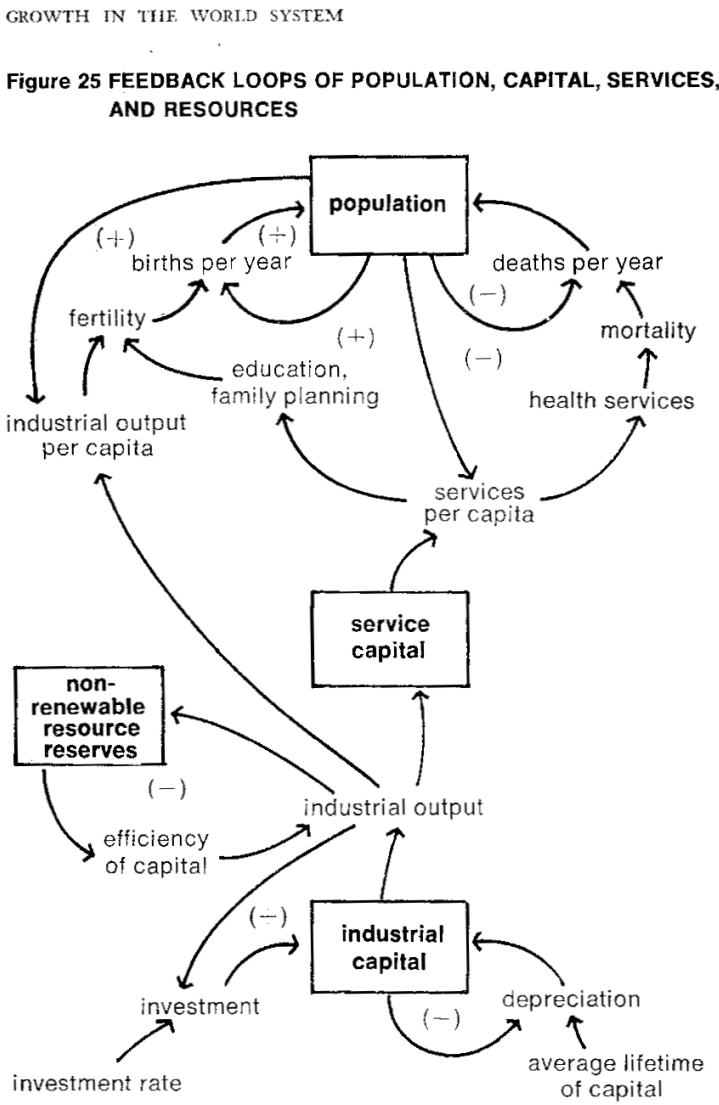
Dynamics of biophysical collapse: limits to growth

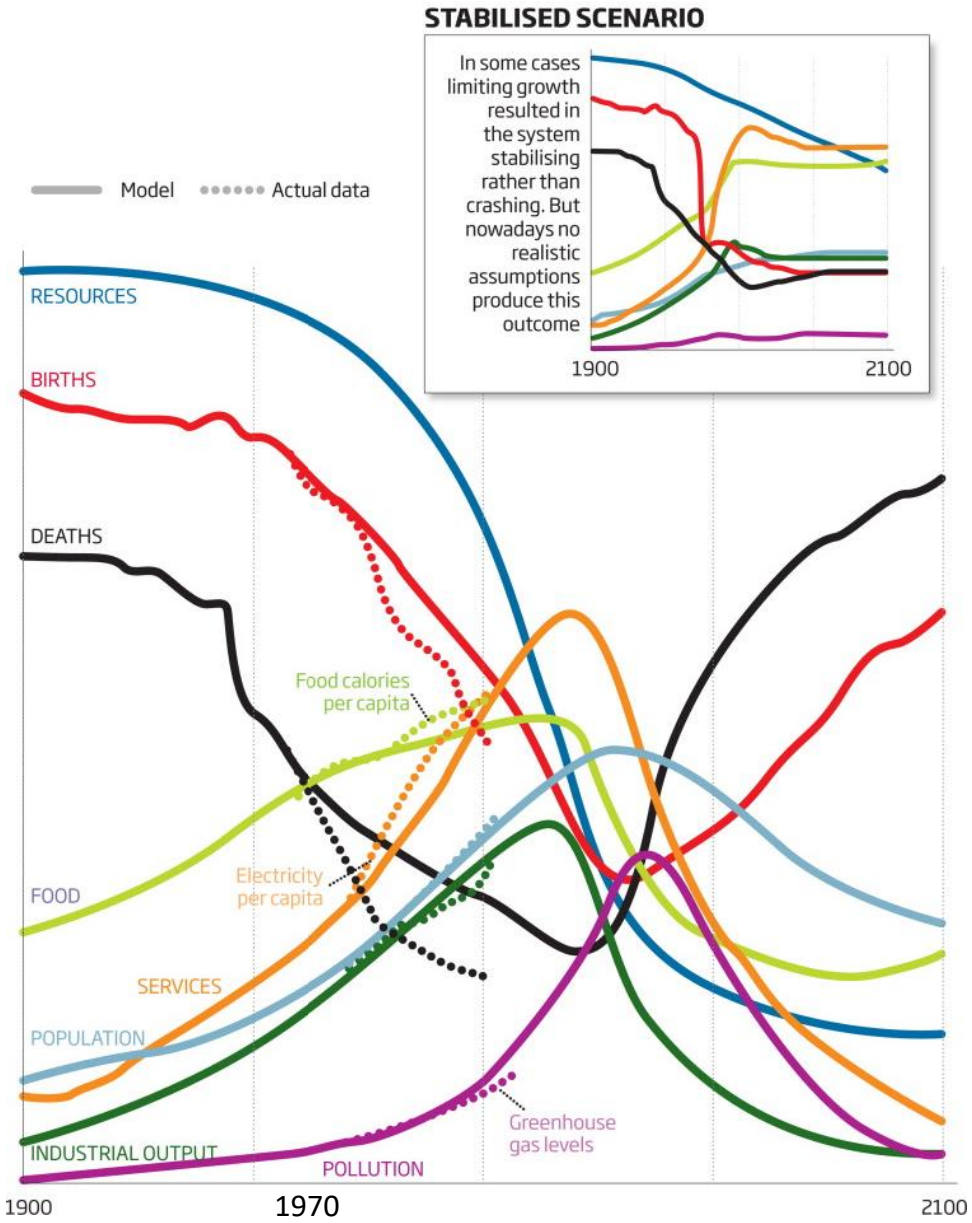


1972



2004





Source: Meadows et al. (1972, 2004)

2. Ecological overshoot

Key takeaways

- 7 of 9 planetary boundaries are transgressed, indicating an ongoing planetary crisis, suggesting a systemic problem
- The 6th mass extinction of life is ongoing
- Climate change already has global consequences
- Warming and extreme weather events will increase in frequency and intensity
- This will have multiple consequences on human and ecosystems health, infrastructures, crop yield…
- Fossil fuels supply, the blood of our modern societies (84% dependent), will fall short soon in Europe regardless of our climate policy
- Our development model is unsustainable. We must rapidly end our overshoot situation to avoid biophysical collapse.

So…

What must be done?

3.

TRANSFORMATION PATHWAYS

Towards a good life for all within planetary boundaries?

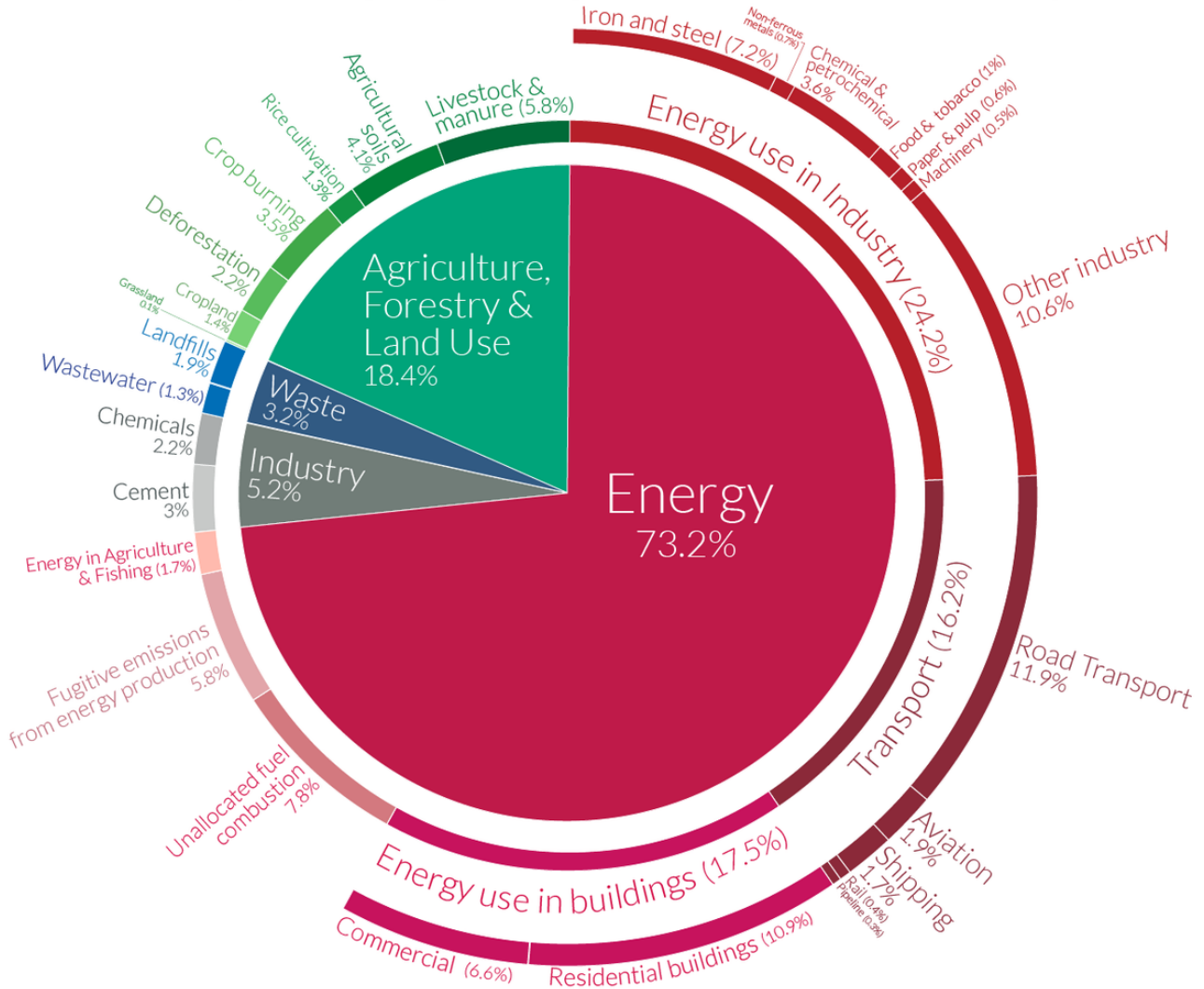
“What we do between 2020 and 2030 will be the decisive decade for humanity's future on earth”

Professor Johan Rockström, PID Director

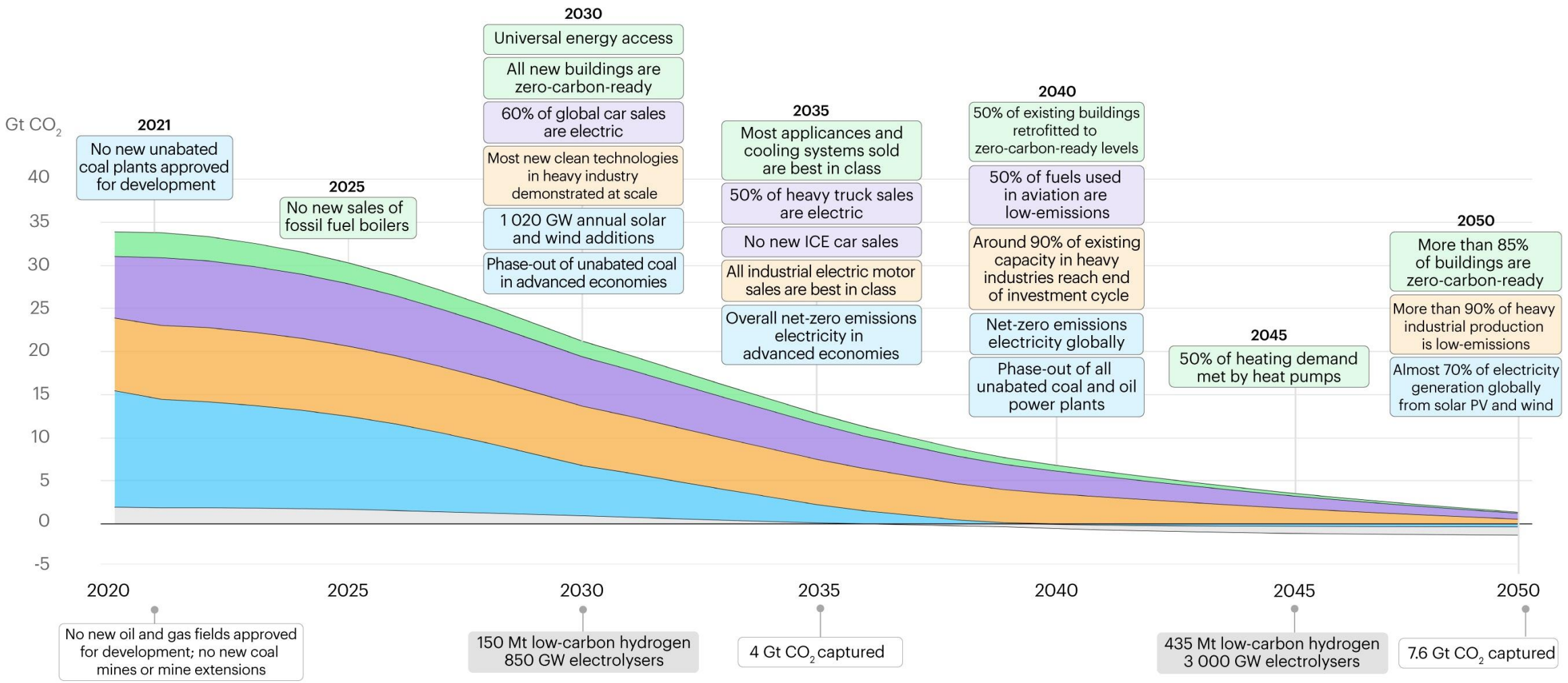
Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2eq.

Our World in Data

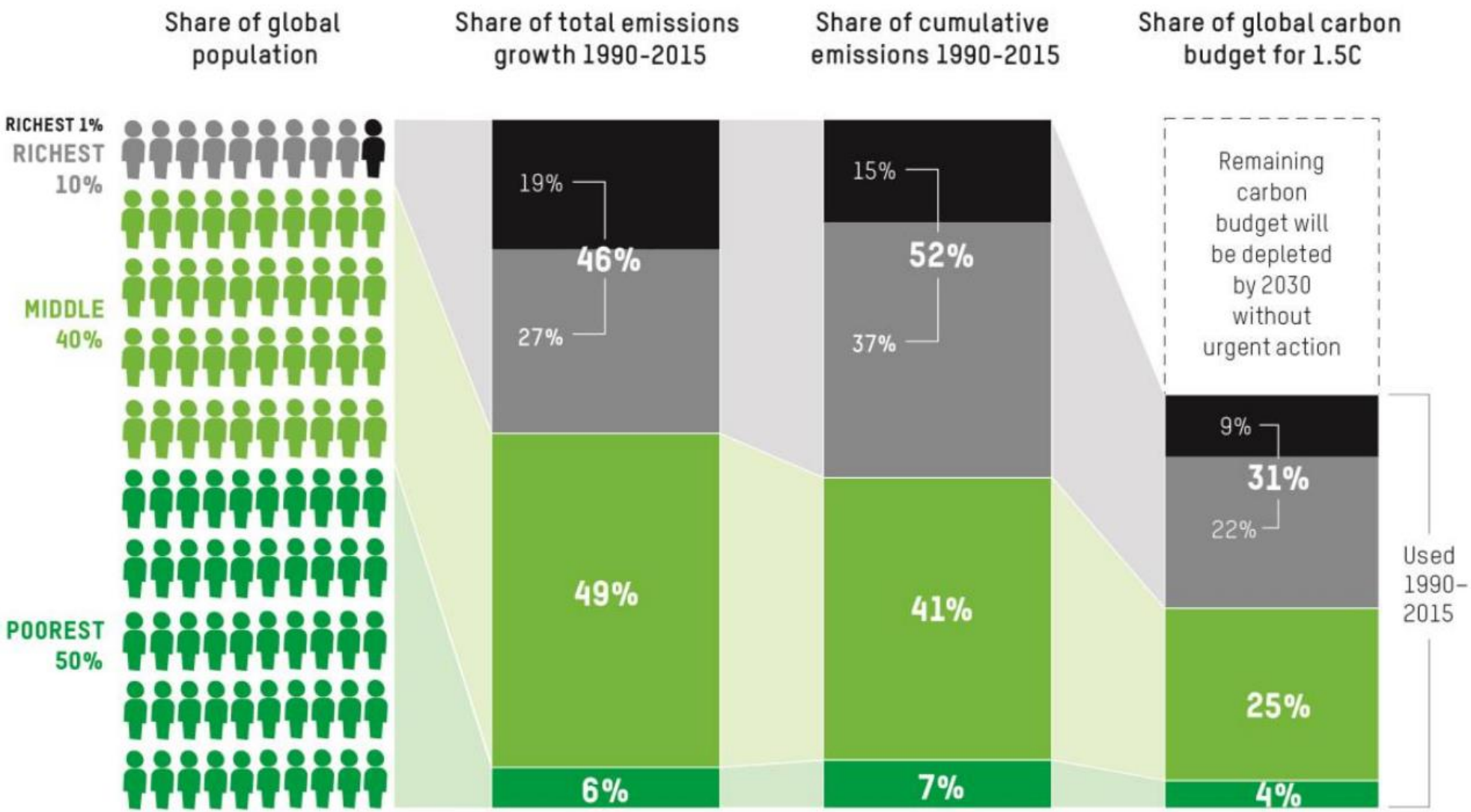


Key milestones in pathway to net zero



Source: IEA

Carbon inequality between socio-economic groups



Source: Oxfam

3. Transformation pathways

Key takeaways

- GHG emissions must rapidly decline and reach net zero by 2050-2070 to limit warming to 1.5-2°C, but they keep increasing.
- This can be done by
  - Reducing emissions (decarbonization, efficiency, sufficiency)
  - Developing anthropic sinks
- GHG emissions mainly come from the burning of fossil fuel
- A transition is required from fossil fuels to low-carbon sources combined with a widespread electrification of end uses
- Although they made outstanding progress, low carbon technologies will need to be deployed at very high paces to meet climate targets
- There are severe carbon inequalities, and those with the lowest responsibility tend to be the most vulnerable to climate change, leading to climate injustice
- The rate of emissions decline has been highly insufficient in OECD countries mainly due to increase in consumption (GDP)
- Climate mitigation present some trade-offs with other environmental pressures, but major co-benefits

So…

Why aren't we on track?

4.

ROOT CAUSES OF OUR INADEQUATE RESPONSES

Cultural, political and economic brakes to transformational change

"If the only tool you have is a hammer, you tend to see every problem as a nail"

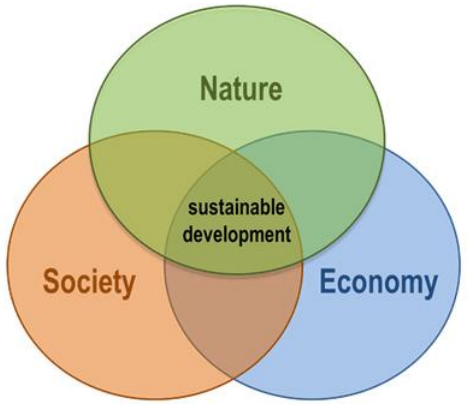
Abraham Maslow, psychologist

"Anyone who thinks that you can have infinite growth in a finite environment is either a madman or an economist"

Kenneth Boulding, founding father of ecological economics

This leads to differentiated sustainability strategies

Weak sustainability



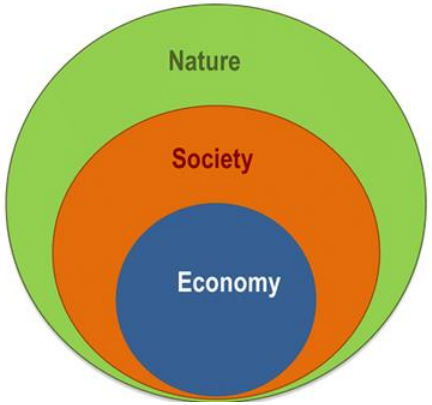
Weak sustainability/ modernity paradigm

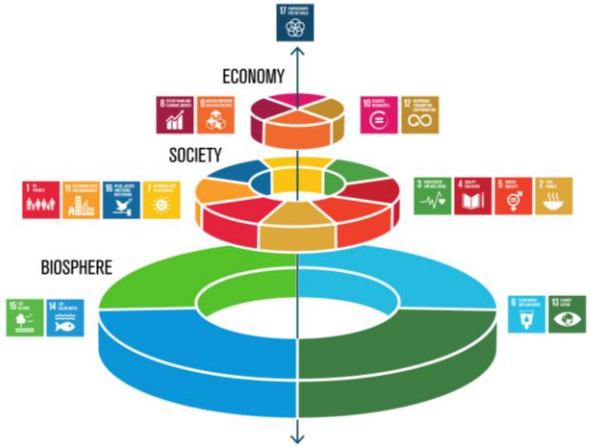
Status quo
Technological fix with minor or no changes to lifestyle choices
Prioritise economic issues; deal with environmental issues as needed
Technical progress and optimism

Perfect substitution of natural and manmade capital
Manage business risk within existing free-market system

Source: adapted from Ehrenfeld (2000).

Strong sustainability





Strong sustainability/ sustainability paradigm

Transformation
Fundamental reassessment of values and lifestyle choices
Integrated, holistic approach to three dimensions

Technological scepticism and precautionary principle
Limited substitution of natural and manmade capital
Transform market system

Source: Stockholm Resilience Center

4. Root causes of our inadequate responses

Key takeaways

- The role of technology in addressing environmental problems:
  - Has presently been limited by rebound effects and by inadequate use driven by consumerist mindset
  - Slowed by past choices that have created socio-technical lock-ins
  - Is generally overstated: technosolutionism
- Consumerism has been constructed to fulfill the growth imperative of a capitalist economy
- Information on environmental problems:
  - The fossil fuel industry has perpetrated disinformation, propaganda and lobbying campaign to delay climate action, leading to climate denial
  - Media coverage has been highly problematic both in terms of time dedicated and way of depicting the issue
- The inadequate description of the role of the environment in mainstream economics led to inadequate tools and sustainability strategies
- Biophysical descriptions of the economy enable the derivation of new tools for guiding human development

So…

What else can go wrong?

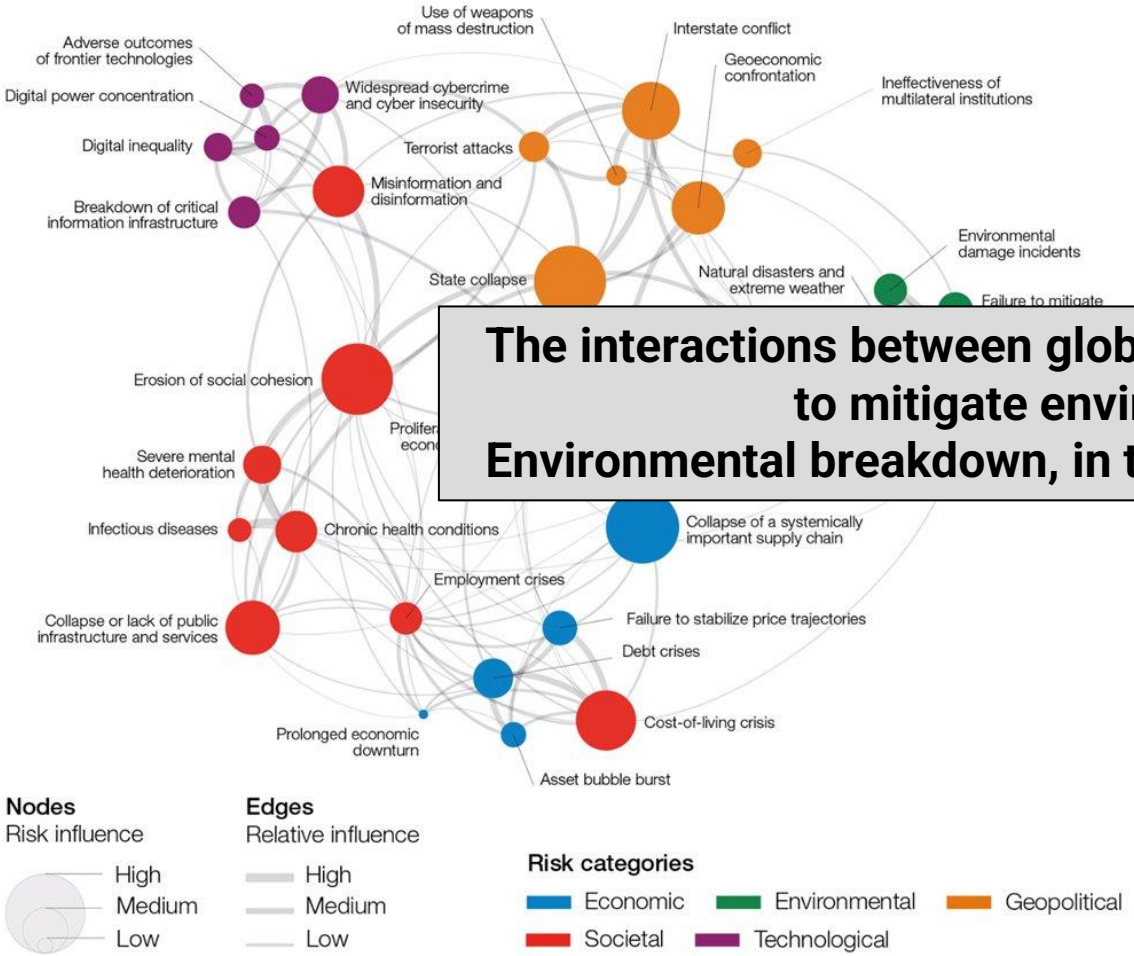
5.

CHALLENGES ALONG THE WAY

Global systemic risks on the road to net zero

Global Risks Report 2023

Global risks landscape: an interconnections map



The interactions between global systemic risks threaten our ability to mitigate environmental breakdown.
Environmental breakdown, in turn, makes these risks more severe.

Source: World Economic Forum, Global Risks Perception Survey 2022-2023

Global Risks Report 2023

Top 10 Risks

"Please estimate the likely impact (severity) of the following risks over a 2-year and 10-year period"

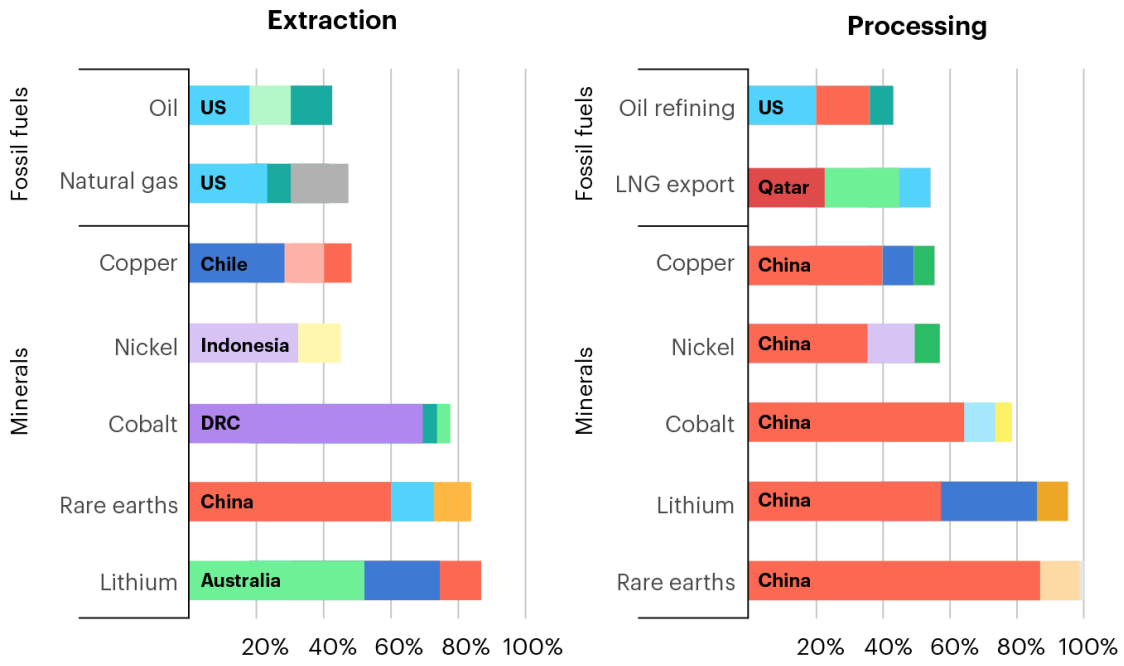
	2 years	10 years
1	Cost of living crisis	Failure to mitigate climate change
2	Natural disasters and extreme weather events	Failure of climate-change adaption
3	Geoeconomic confrontation	Natural disasters and extreme weather events
7	Failure of climate-change adaption	Erosion of social cohesion and societal polarization
8	Widespread cybercrime and cyber insecurity	Widespread cybercrime and cyber insecurity
9	Natural resource crises	Geoeconomic confrontation
10	Large-scale involuntary migration	Large-scale environmental damage incidents

Risk categories
Economic
Environmental
Geopolitical
Societal
Technological

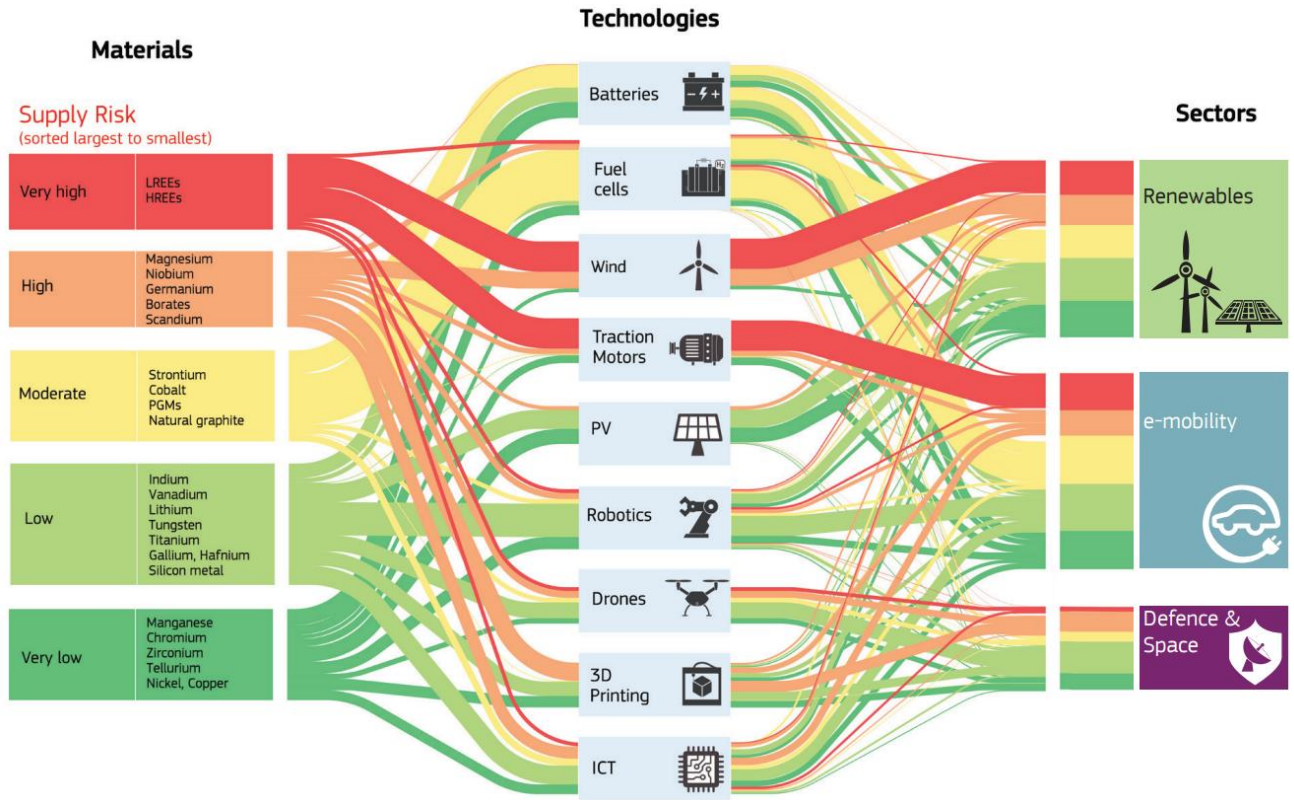
Source: World Economic Forum, Global Risks Perception Survey 2022-2023

Socio-economic and geopolitical dimensions drive raw material ‘criticality’

Share of top 3 producing countries in production of minerals and fossil fuels, 2019



Critical raw materials for the EU



Source: IEA, EU JRC

5. Challenges along the way

Key takeaways

- Modern societies are facing risks caused by the high level of interconnection between different sectors on a global scale and by the consequences of human activities on the environment
- These so-called systemic risks can be economic, geopolitical, environmental, societal and technological
- They can slow or hinder the transformation of our society towards sustainability
- In particular, raw materials fluxes may become a key limiting factor for the energy transition, while global finance may be a significant destabilizer
- Fragile states are also the most vulnerable to climate change, which is an amplifier of tensions potentially leading to armed conflicts

So…

What about the space sector?

6.

WILL WE CONTINUE SPACE ACTIVITIES?

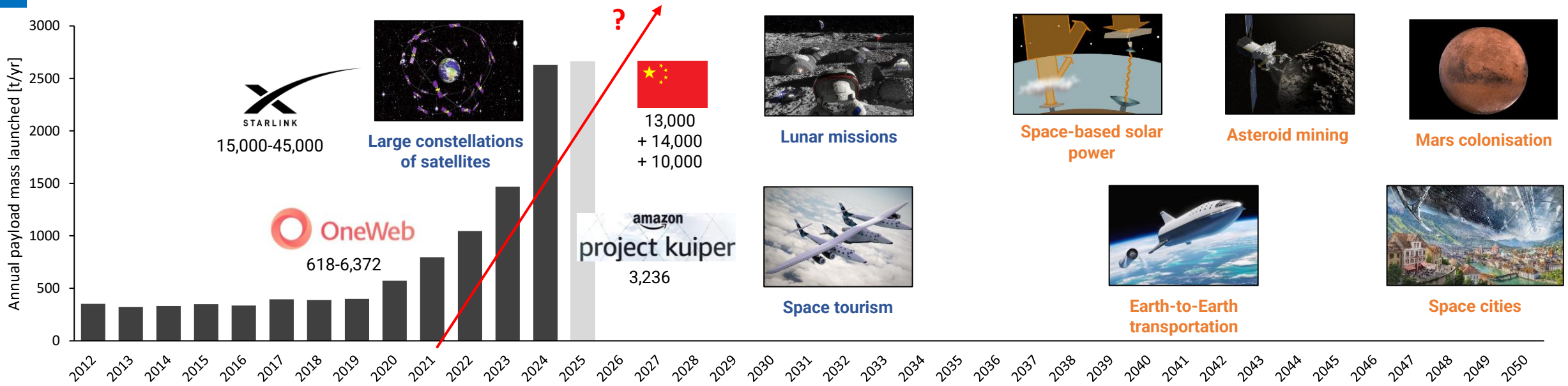
The future of the space sector in the Anthropocene

"Earth is the cradle of humanity, but one cannot live in a cradle forever"
Konstantin Tsiolkovsky

"One day, Mars will save Earth. I am certain of it."
Elon Musk, CEO of SpaceX

"This discussion leads us to the inevitable conclusion that we are bound to the Earth for the next 100,000 years. […]"
Roger-Maurice Bonnet, former ESA scientific director

A new paradigm enabling the development of new space activities and speculative projects…



…in a context of environmental crisis requiring and triggering profound technological and societal transformations

…leading to serious concerns on the environmental sustainability of space activities

THE WALL STREET JOURNAL.
As Rocket Launches Take Off, So Do Concerns About Emissions

Spacecraft Are Sprinkling the Stratosphere with Metal

The New York Times
The New Space Race Is Causing New Pollution Problems
Earth's stratosphere has never seen the amounts of emissions and waste from rockets and satellites that a booming space economy will leave behind.

BBC
The pollution caused by rocket launches

The Guardian
How the billionaire space race could be one giant leap for pollution

BBC Science Focus
Are space launches bad for the environment?
Space rockets may not be very environmentally friendly.

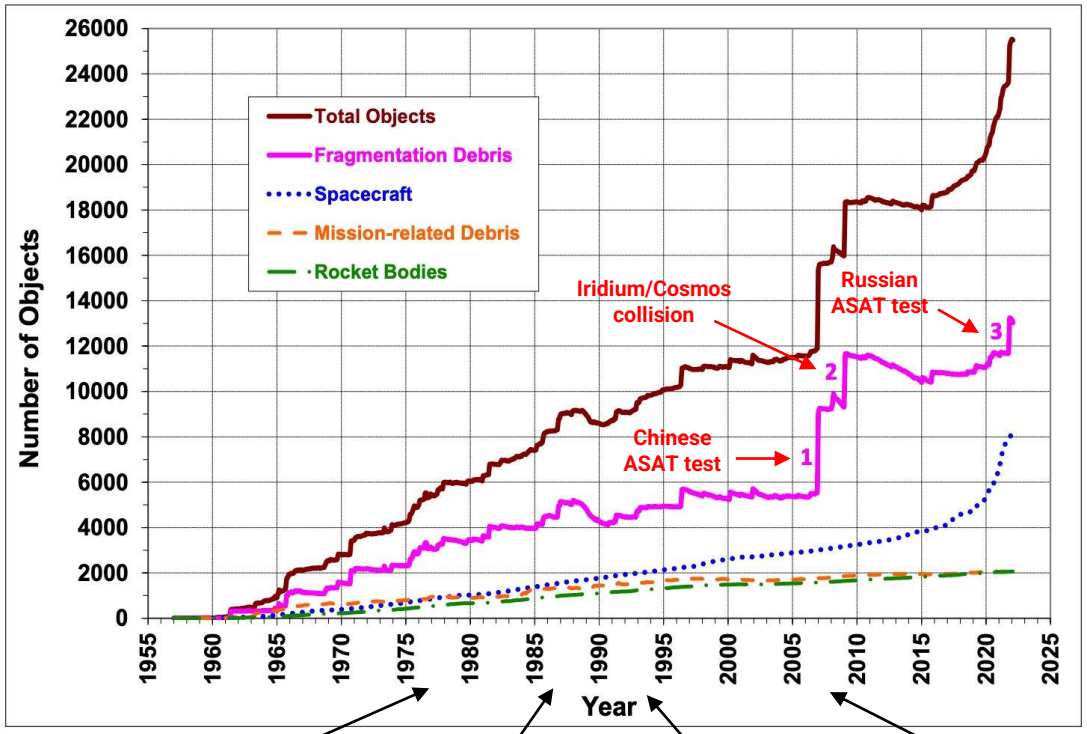
Light pollution from satellites 'poses threat' to astronomy

After SpaceX Starlink Launch, a Fear of Satellites That Outnumber All Visible Stars

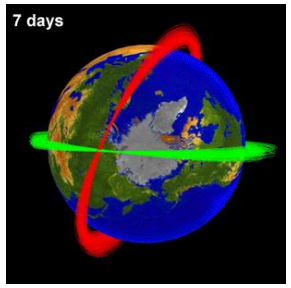
IMPACTS ON THE BIOSPHERE

Pollution of the orbital environment: déjà vu?

Orbital environment trend (space debris growth)

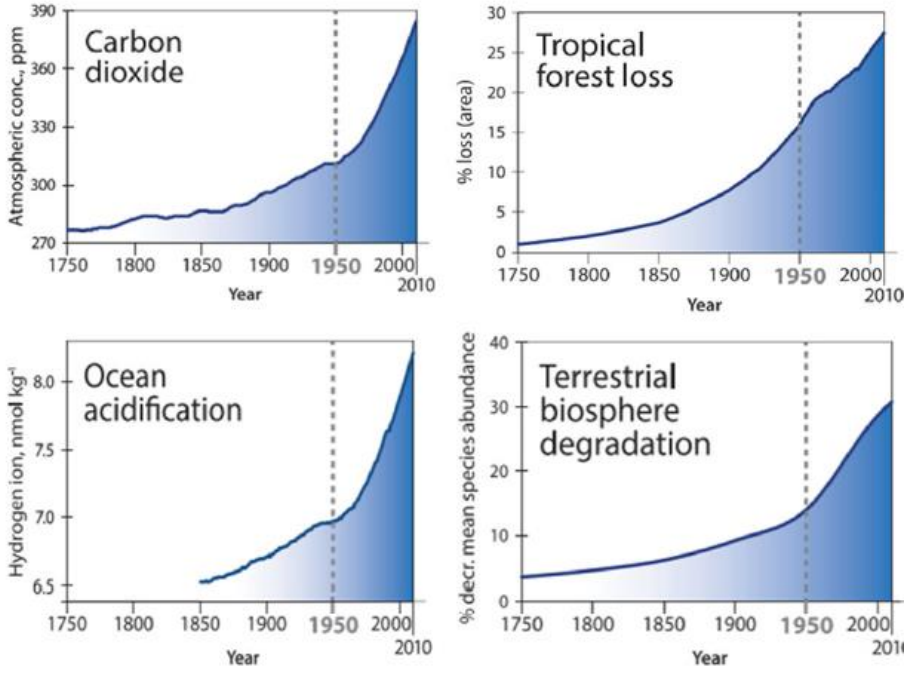


Anti-satellite missile



Satellites collision

Earth system trends (environmental stressors)



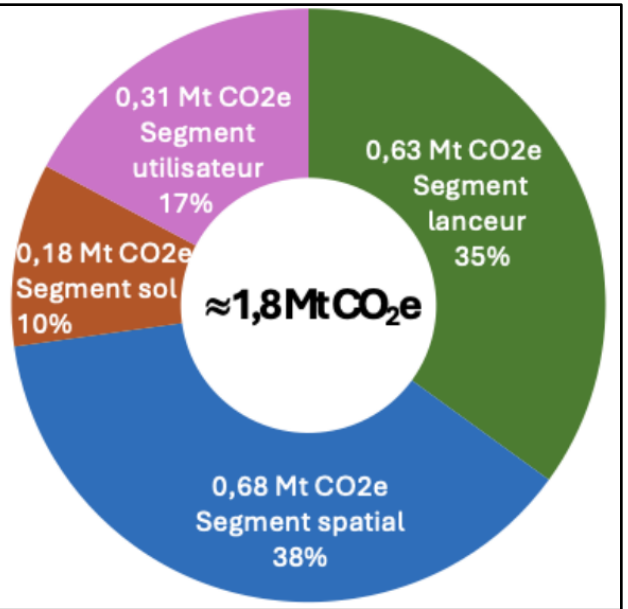
Source: adapted from Maury (2020), NASA

The French space sector's carbon footprint

Répartition de l'empreinte carbone de la filière spatiale française

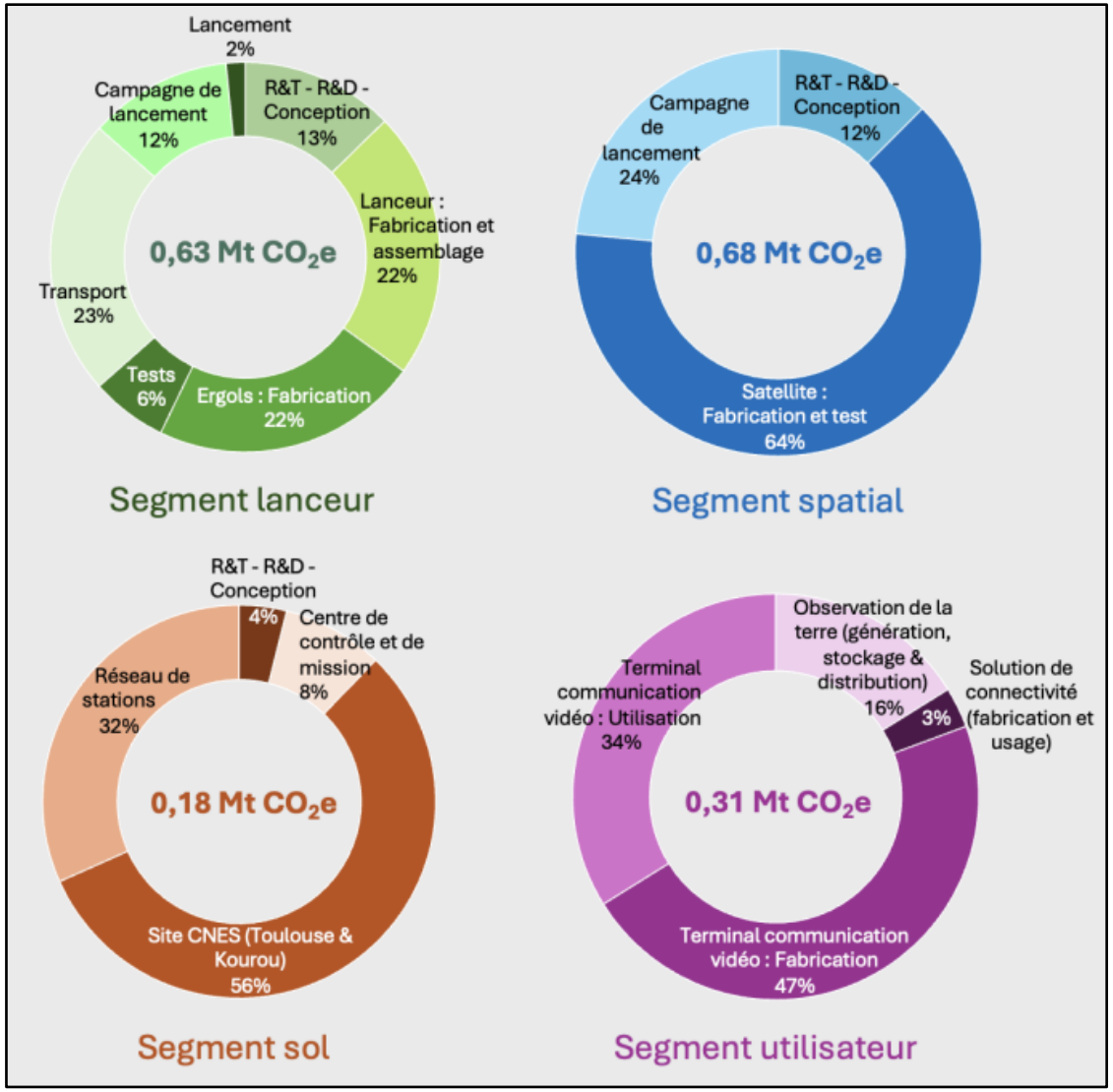
Source : Carbone 4

2023 data



= 0.3% of national French emissions

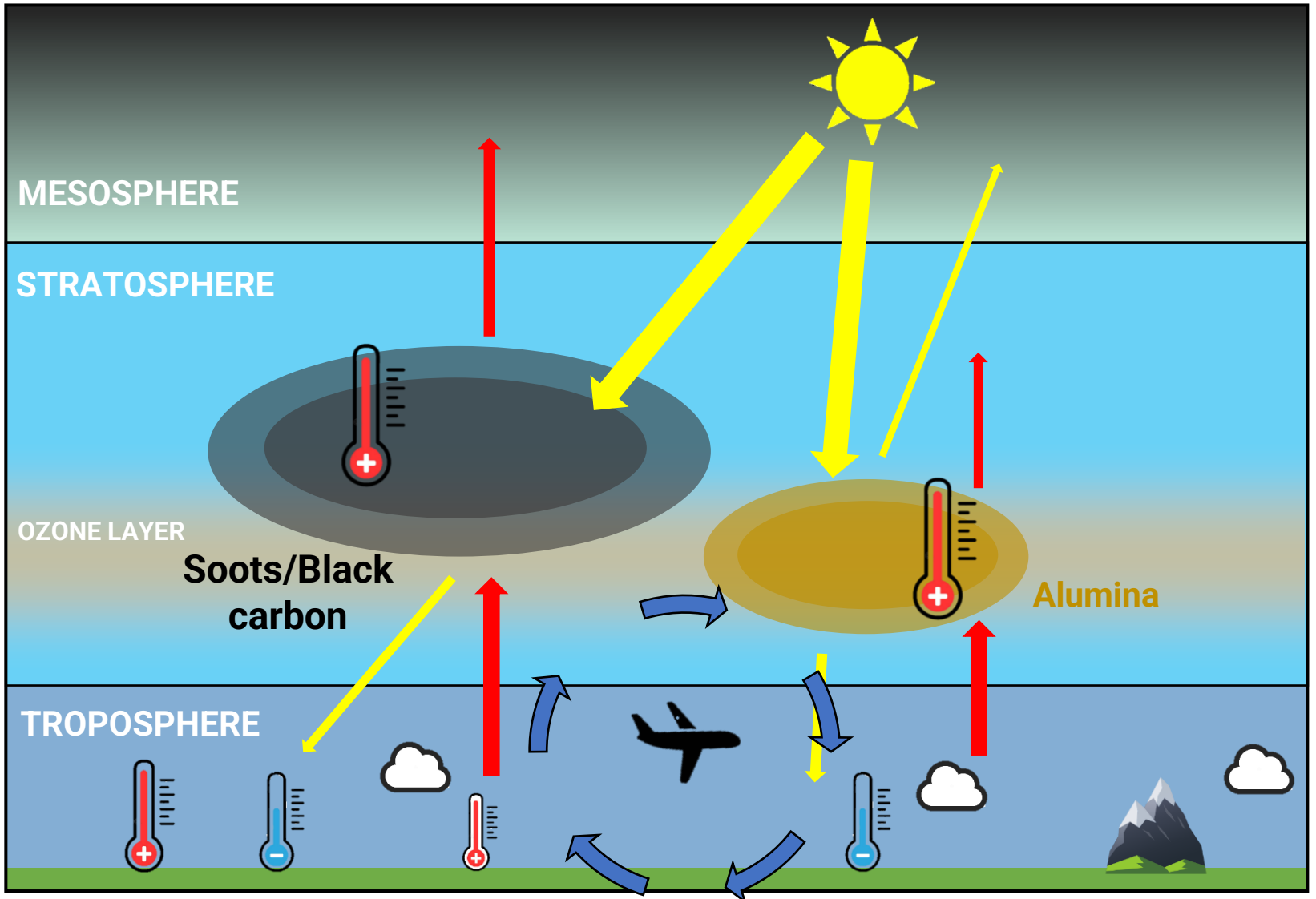
But all of this does not account for the launch event!!



Source: COSPACE

The impacts of rocket launches on the atmosphere

Particles accumulate in the stratosphere and warm it



Accumulation in the stratosphere

Residence time:
Troposphere : a few days
Stratosphere : 3-5 years

↓ Rocket soots **500x** more efficient at warming than other sources of soots

Warming of the stratosphere

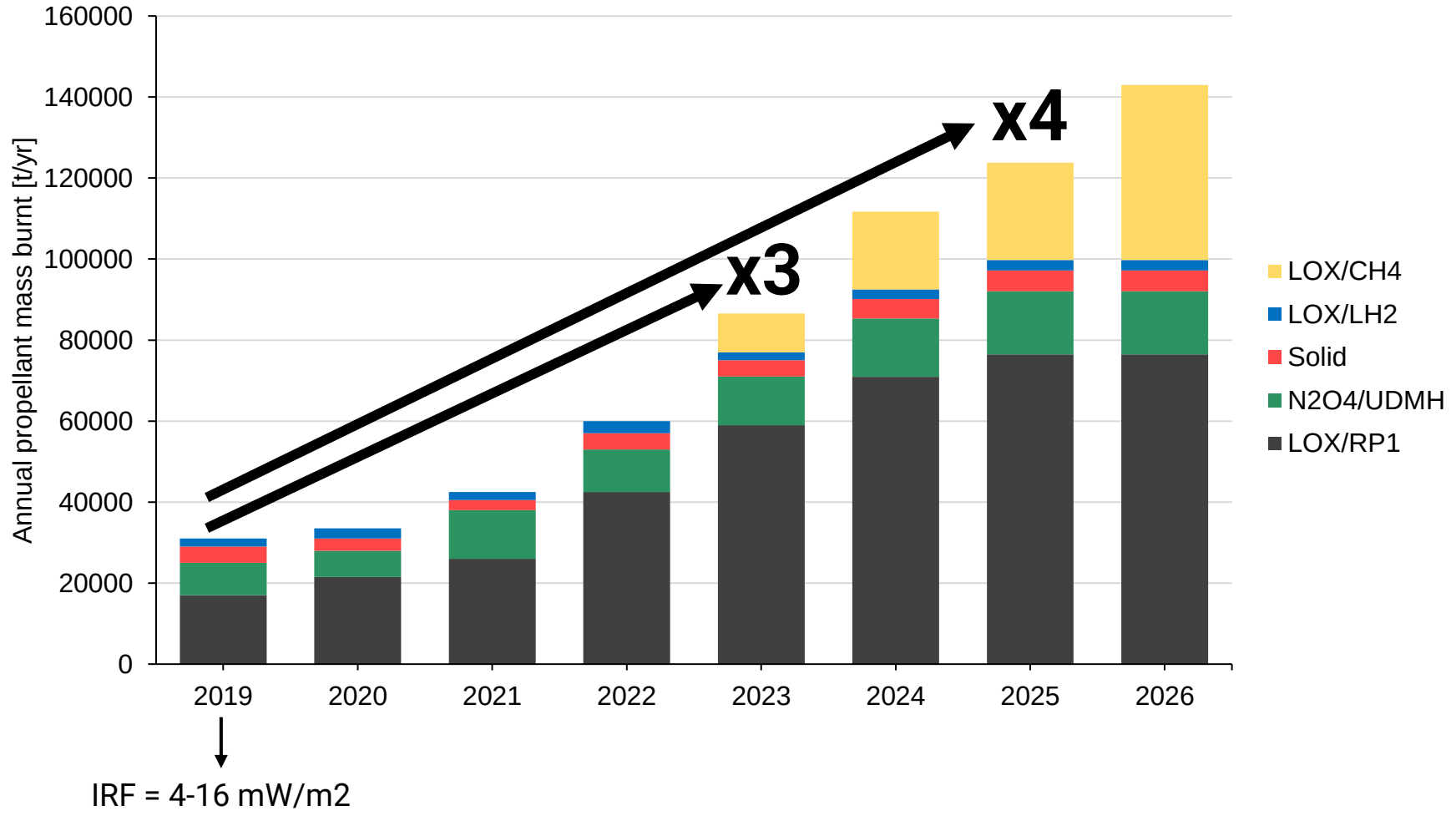
↓ ?

Complex changes resulting in areas of warming and of cooling

Source: Miraux (2021) adapted from Ross & Vedda (2018), Ryan et al. (2022), Maloney et al. (2022)

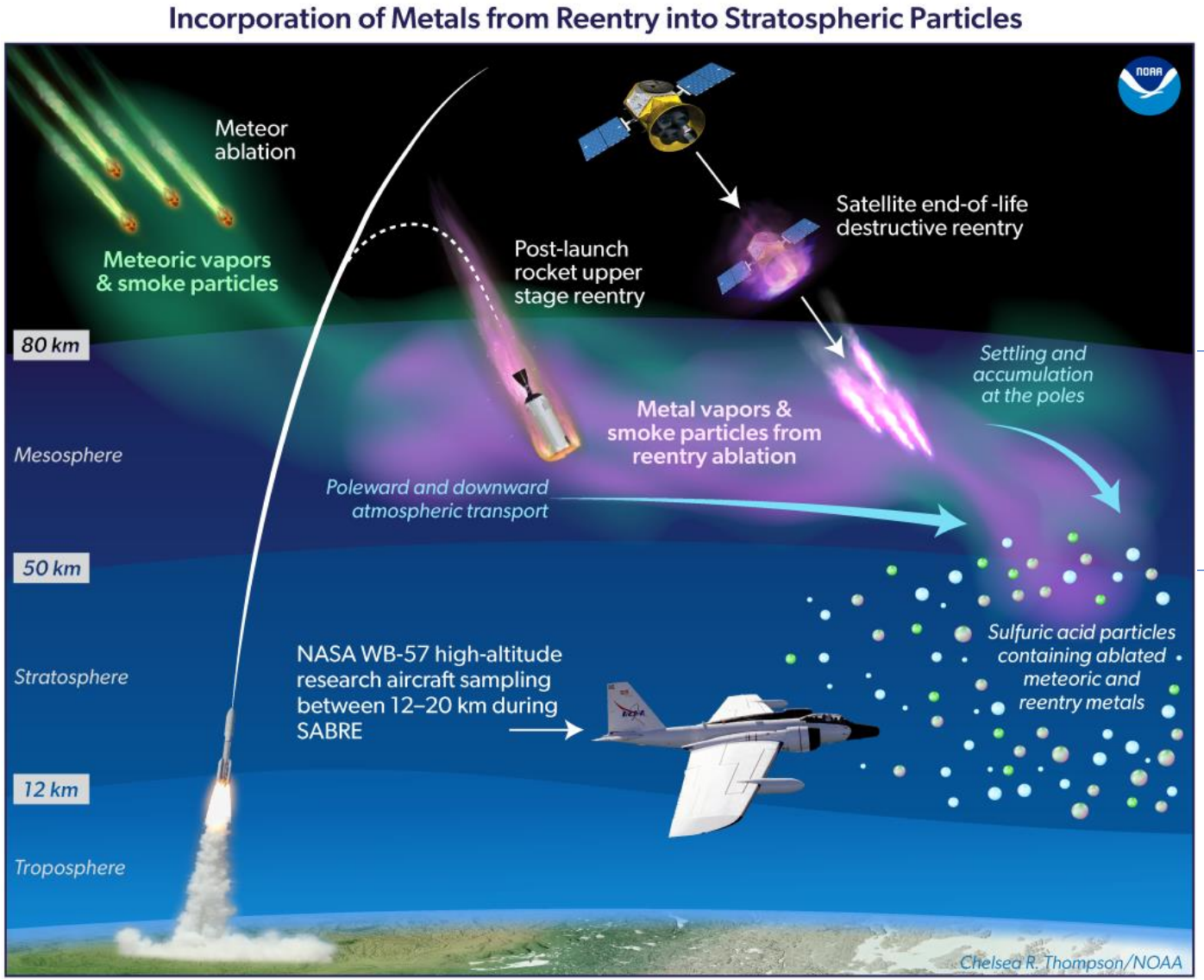
The impacts of rocket launches on the atmosphere

Propellant mass burnt grows fast and is dominated by large particles emitters



Source: DLR, own calculations

The effect of re-entry emissions remains unknown



900 tons of spacecraft material re-entering per year

↓ *Demise*

350 tons of particles injected in the mesosphere

↓ *Migration time to stratosphere ~30y ?*

10% of aerosol particles in the stratosphere contain metal originating from spacecraft re-entry

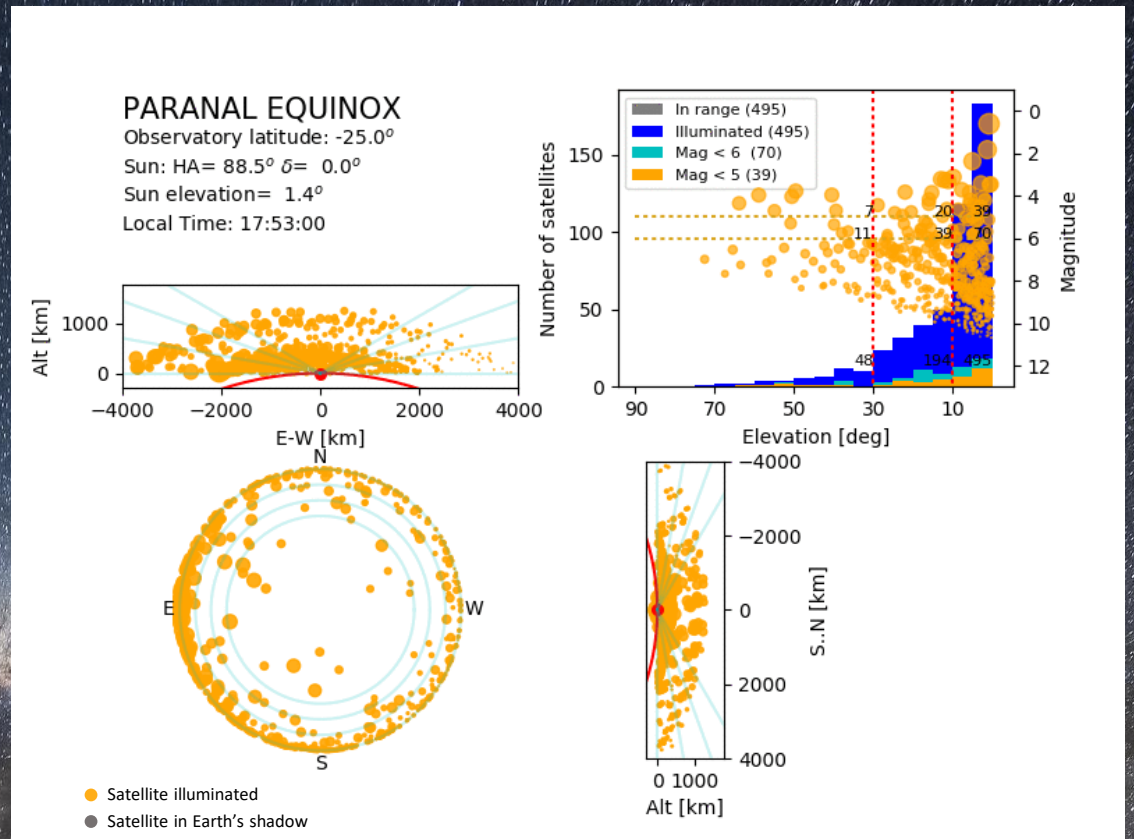
↓ *Ice nucleation, polar stratospheric clouds, catalysis of ozone-destroying reactions*

Effects on climate? Ozone? Unknown!

Depending on constellation deployment scenarios:

- More satellites with smaller lifetimes (~5y)
- **10 kt/yr re-entering; 4kt injected,** aluminum injection **15x natural level**
- 'High' Starlink only scenario: 45,000 V2&3 ; full reusability ➔ **10 kt/yr re-entering**

Source: Shultz & Glassmeier (2021), Miraux et al. (2022), Murphy et al. (2023), Ferreira et al. (2024)



How many satellites at any time?

Starlink Gen1&2 + OneWeb

Above horizon:

- ~100 today
- ~2000 then

Above 30°

- ~10 today
- ~200 then

Visible with naked eye

- 2-3 today
- 5-50 then

Starlink Gen1&2 + OneWeb + Kuiper + GuoWang

In worst case situation, 1 in 15 points will be a satellite

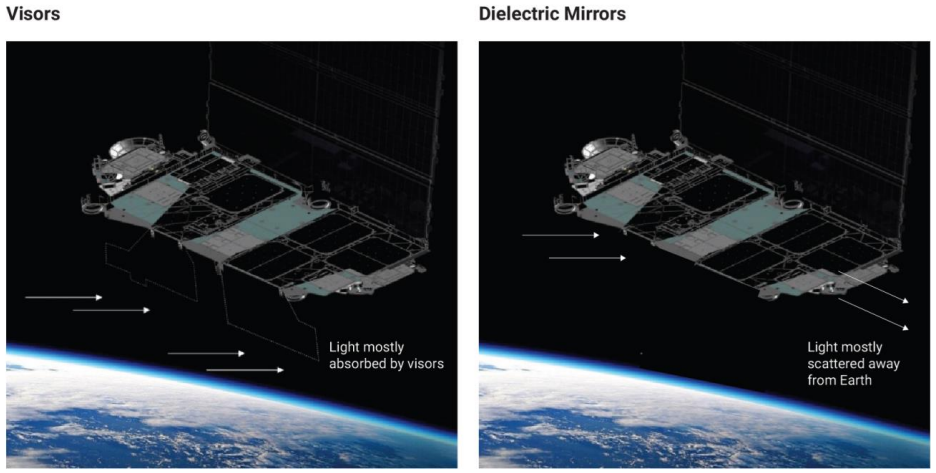
➔ **Satellites will not outnumber visible stars… but their number will soar!**

Source: ESO, Hainaut & Williams (2020), Lawler et al. (2022)

Starlink's mitigation attempts: a mixed outcome

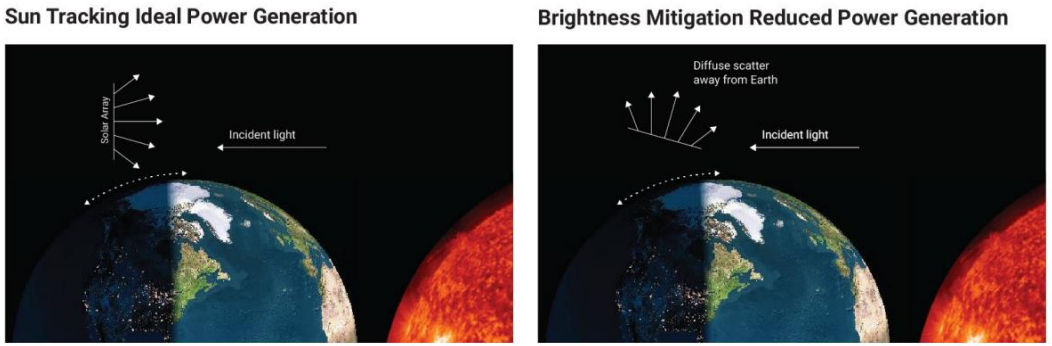
Operations: change of attitude during ascent ➔ 10x fainter during this phase

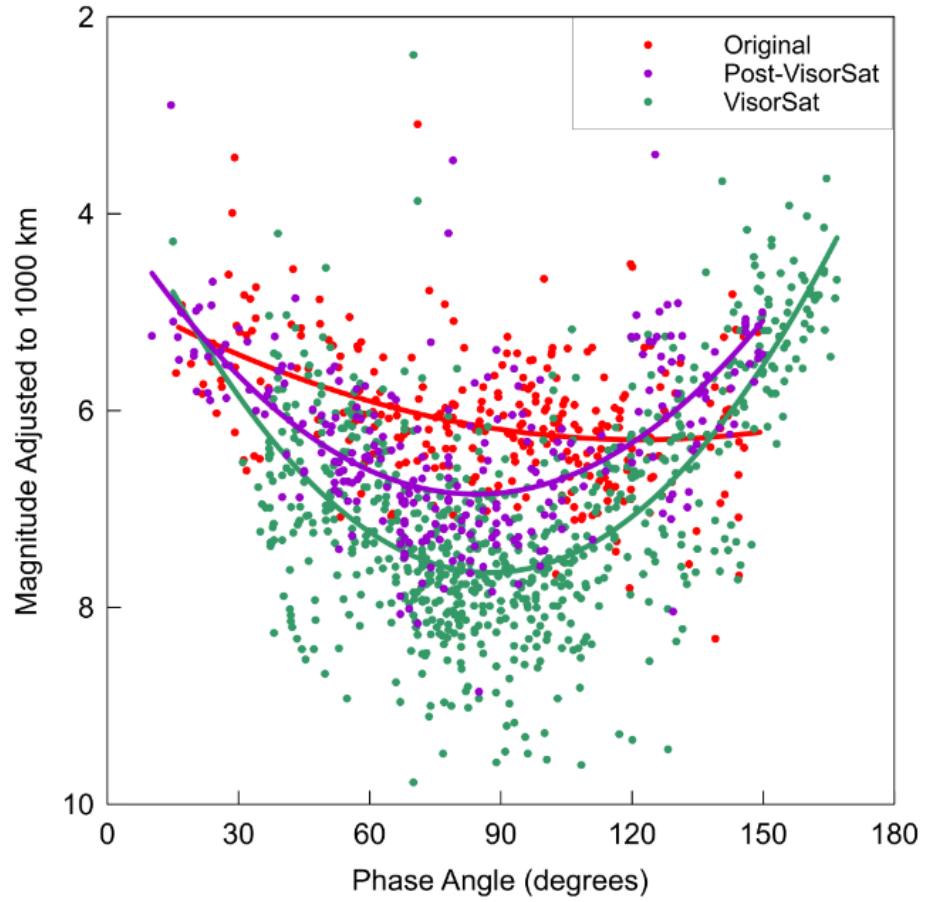
VisorSat: Sun visors to hide solar panels or antennas ; 1st generation dielectric mirrors; Darker solar arrays



Increases drag, prevents laser communication, reduces solar array performance ➔ abandoned

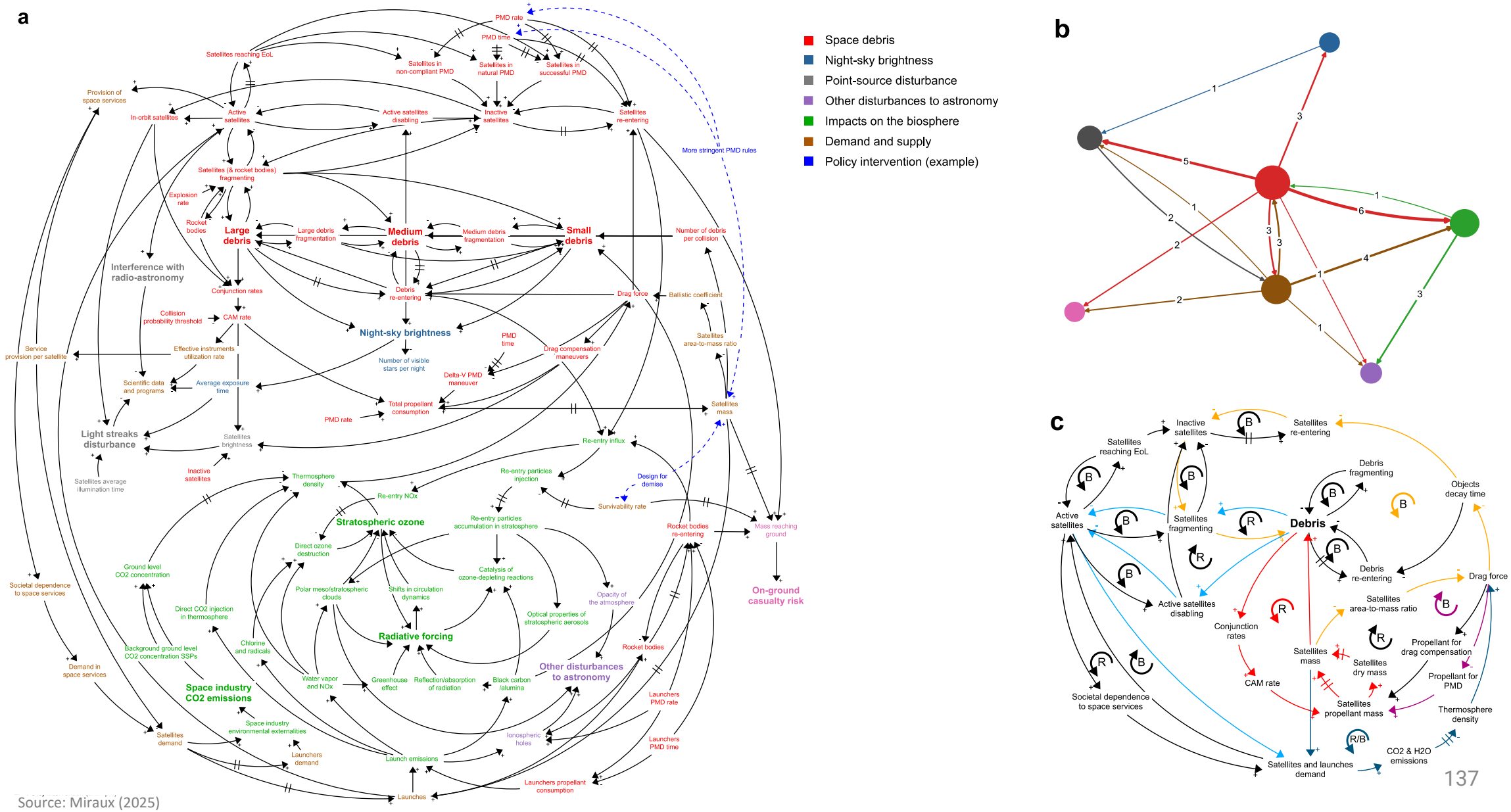
Post-VisorSat: 2nd generation dielectric mirrors; opaque solar arrays backside; off-pointing maneuveurs for solar panels; black paint





Source: O. Hainaut, SpaceX, Mallama et al. (2023)

Causal relationships in the Earth-space sustainability system



Source: Miraux (2025)

6. Will we continue space activities?

6.1 The environmental footprint of space activities

Key takeaways

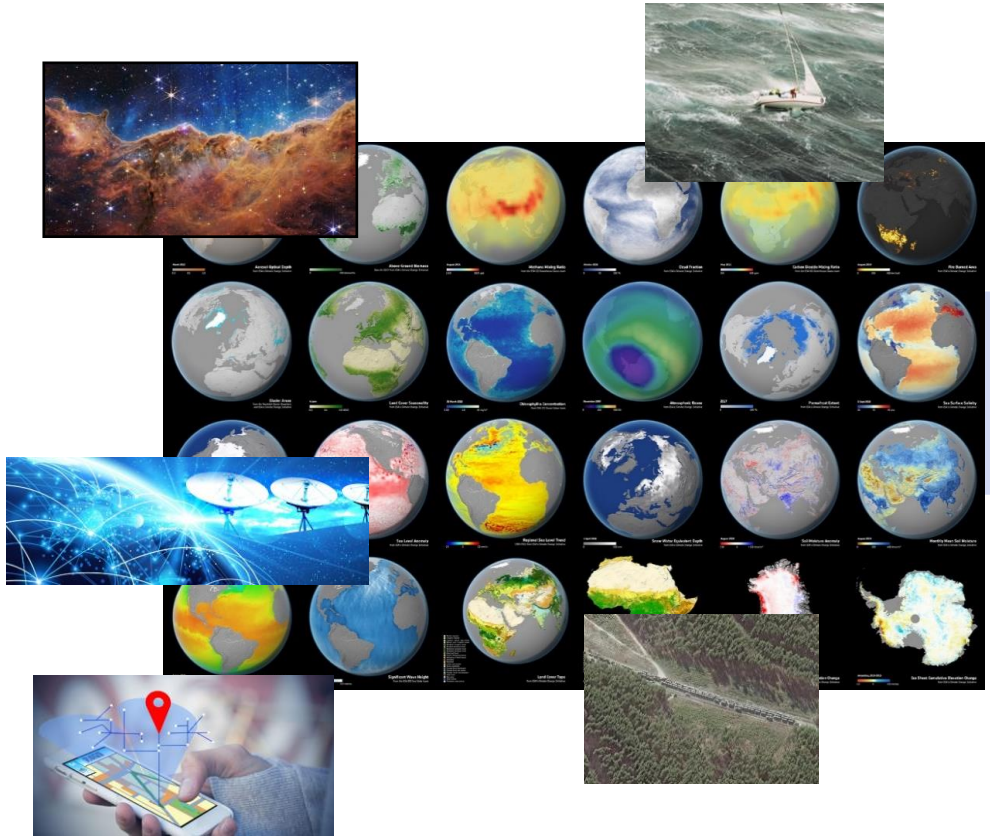
- The space sector is a new frontier for environmental science, featuring unique impacts that can involve highly complex physics.
- Although space debris has been long identified as a threat, the number of debris will continue to grow even if we stop launching.
- Light (optical and radio) pollution from satellites pose a serious threat to astronomy and its impacts are not fully understood yet.
- The impacts of the space industry on climate and ozone are dominated by launchers because of their emissions – mainly particles – in the upper atmosphere. Re-entry may also be an issue. Both are not well understood yet, especially re-entry.
- These impacts are interacting and mitigation attempts will face complex trade-offs. They must be tackled using systems thinking.
- The impacts of the industry can rapidly become concerning as it grows very fast. The environmental costs of large-scale projects requiring high launch rates likely exceed by far their benefits.

So…

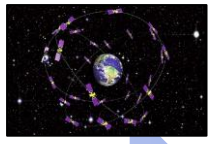
What can we do about it?

Towards additional and more intense ecological impacts… for which societal benefits?

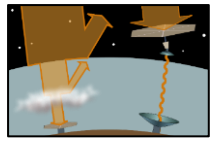
‘Historical’ space



New activities and promises

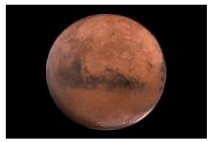


Large constellations of satellites
Global broadband connectivity for all!



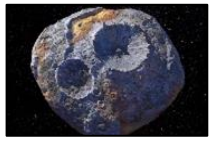
Space-based solar power
Clean energy to help meet our climate targets!

Earth-to-Earth transportation
Everywhere on Earth in under an hour!



Mars colonisation
Planet B!

Space tourism
Space is for all humanity!



Asteroid mining
Unlimited resources!

Space cities
Planet B!

Narratives and promises that should be questioned given what we know now!

6. Will we continue space activities?

6.2 What space activities in the Anthropocene?

Key takeaways

- The space sector is not one single entity. Space activities have many different objectives and provide various services to society. Their motivation may also often be driven by complex and intricated issues of geopolitics, economics, sovereignty, and ideology. Any critical analysis should account for that.
- Earth observation from space has been essential for environmental science and policy and will continue to be.
- Modern society is strongly dependent on many services provided by satellites, but their development must be questioned, and telecommunications in particular since it will likely be the one generating the most impacts in the near future.
- Space tourism exacerbates environmental inequalities due to an unparalleled combination of economic inaccessibility and outstandingly high environmental footprints per passenger.
- Projects aiming at increasing the carrying capacity of humans with space resources/habitat are dangerous distractions with high ecological costs.
- The space sector is vulnerable and its development will be undermined by global socio-environmental crises.

So…

What do you think?