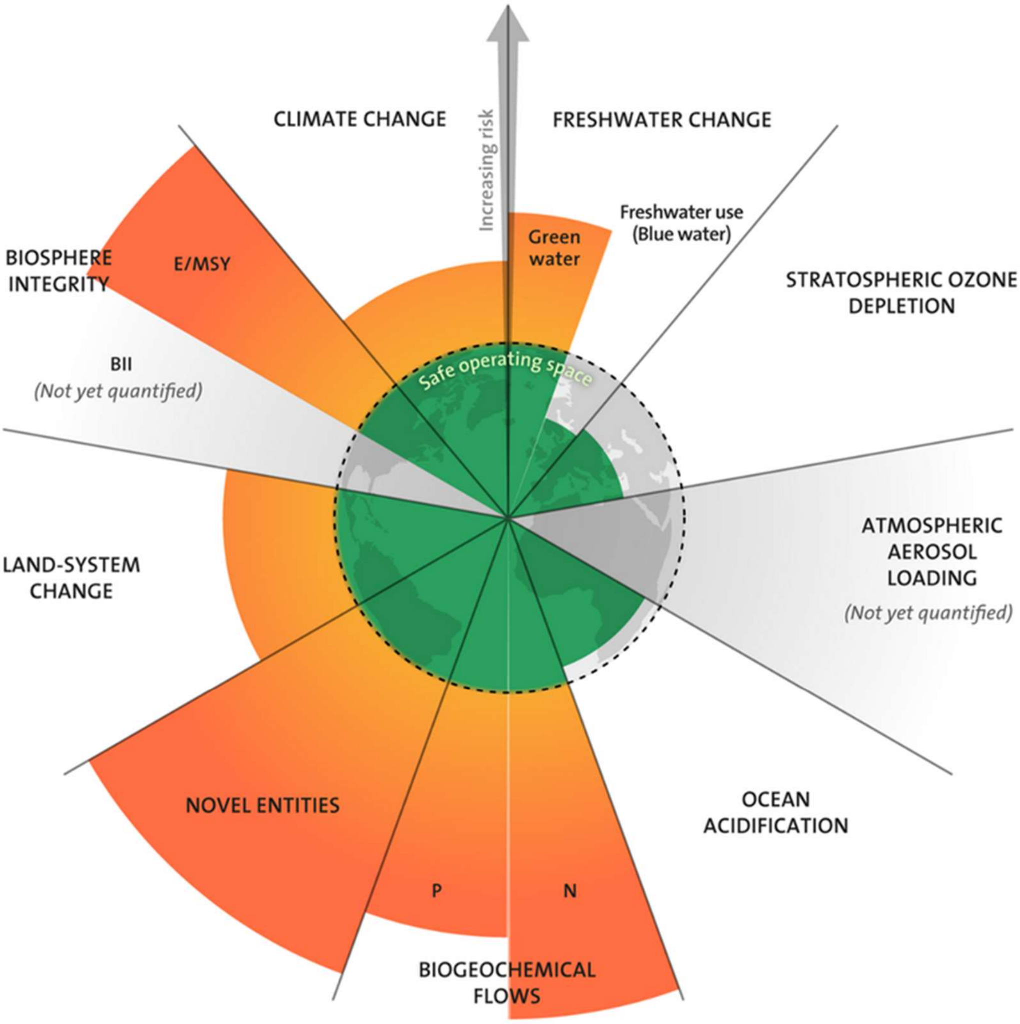

Planetary Boundaries

By Maria Eugenia Fernández de Caveda Perez

Objective of this course:

What will you learn, analyze, study, or apply with in this course and with what purpose?

Student will learn what are the Planetary boundaries and their importance for the adequate functioning of all Earth Systems.

Course Description:

What areas of study will you cover on this course? What's the course about?

In this course students will learn about each of the planetary boundaries, what is the transgression estate right now and what can be done so humanity can thrive without exceeding or transgressing the planetary boundaries.

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Introduction

Although Earth has undergone many periods of significant environmental change, the planet's environment has been unusually stable for the past 10,000 years. This period of stability — known to geologists as the Holocene — has seen human civilizations arise, develop, and thrive. Such stability may now be under threat. Since the Industrial Revolution, a new era has arisen, the Anthropocene, in which human actions have become the main driver of global environmental change. This could see human activities push the Earth system outside the stable environmental state of the Holocene, with consequences that are detrimental or even catastrophic for large parts of the world (Nature, 2009).

In 2009, there were two key publications about Planetary Boundaries:

Ecology & Society: Planetary Boundaries: Exploring the Safe Operating Space for Humanity

Nature: a special section and feature article published in Nature

Planetary Boundaries

The planetary boundary (PB) framework, introduced in 2009 by a group of scientists, led by Professor Johan Rockström, aimed to define the environmental limits within which humanity can safely operate. Researchers quantified the boundaries that influence Earth's stability (Science for environment policy, 2015).and associated thresholds which, if crossed, could generate unacceptable environmental change. Researchers found nine such processes and defined nine planetary boundaries: climate change; rate of biodiversity loss (terrestrial and marine); interference with the nitrogen and phosphorus cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; change in land use; chemical pollution; and atmospheric aerosol loading (nature, 2009).

The table below shows the nine planetary boundaries and those which were already exceeded by 2009. As well as the proposed boundary by the researchers, the current status by 2009 and the comparative pre-industrial value.

PLANETARY BOUNDARIES				
Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis		To be determined	
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof		To be determined	

Boundaries for processes in red have been crossed. Data sources: ref. 10 and supplementary information

Figure 1 - Planetary Boundaries *(Nature, 2009).*

In this article from the Nature journal (2009), researchers analyzed those planetary boundaries that had already been transgressed: Climate change, Rate of Biodiversity loss and Nitrogen cycle.

1. Climate Change

Anthropogenic climate change is now beyond dispute. The international discussions on targets for climate mitigation have intensified. There is a growing convergence towards a '2 °C guardrail' approach, that is, containing the rise in global mean temperature to no more than 2 °C above the pre-industrial level.

The proposed climate boundary is based on two critical thresholds that separate qualitatively different climate-system states.

1. Atmospheric concentration of carbon dioxide.

   Proposal: human changes to atmospheric **CO_2 concentrations should not exceed 350ppm** (parts per million) by volume.

2. Radiative forcing (the rate of energy change per unit area of the globe as measured at the top of the atmosphere) (Watts per m2).

   What is radiative forcing? The influence of a factor that can cause climate change, such as a greenhouse gas, is often evaluated in terms of its radiative forcing. Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. When radiative forcing from a factor or group of factors is evaluated as positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system. In contrast, for a negative radiative forcing, the energy will ultimately decrease, leading to a cooling of the system (IPCC, 2007).

   Proposal: **radiative forcing should not exceed 1 watt per m2** (square meter) above pre-industrial levels.

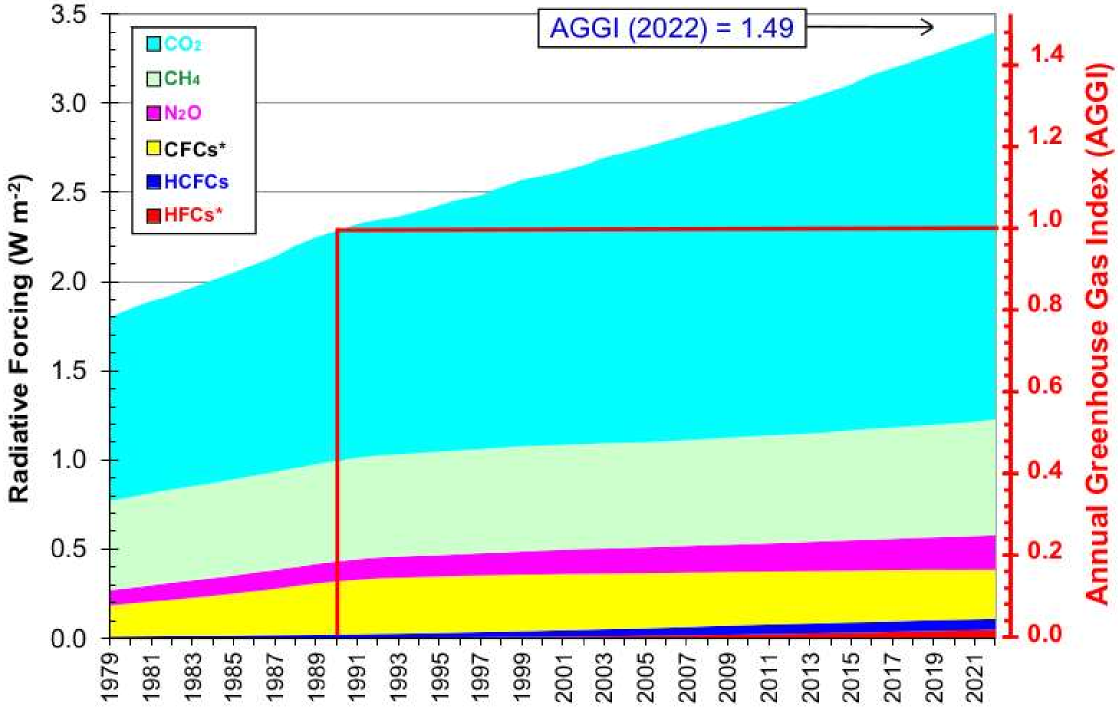

Figure 2 - Radiative forcing for CO_2, CH_4, N_2O and groupings of gases that capture changes predominantly in the CFCs, HCFCs, and the HFCs through 2022. (The NOAA Annual Greenhouse Gas Index (AGGI)).

The Annual Greenhouse Gas Index (**AGGI**) is calculated as the ratio of total direct **radiative forcing** due to these gases each year to its total in 1990.

We can appreciate in the Figure above that Carbon dioxide is by far the largest contributor to total forcing from these gases and methane is the second largest contributor. CO_2 is responsible for about two-thirds of the radiative forcing among all greenhouse gases.

The atmospheric abundance and radiative forcing of the three main long-lived greenhouse gases continue to increase in the atmosphere.

Consequences of transgressing these boundaries: the risk will increase of irreversible climate change (loss of major ice sheets, accelerated sea-level rise and abrupt shifts in forest and agricultural systems).

2. Rate of Biodiversity Loss

Biodiversity loss in the Anthropocene has accelerated massively. Species are becoming extinct at a rate that has not been seen since the last global mass-extinction event. The rate of extinction of species is estimated to be 100 to 1,000 times more than what could be considered natural.

As with climate change, human activities are the main cause of acceleration. Changes in land use exert the most significant effect. These changes include the conversion of natural ecosystems into agriculture or into urban areas; changes in frequency, duration or magnitude of wildfires and similar disturbances; and the introduction of new species into land and freshwater environments.

Biodiversity loss occurs at the local to regional level, but it can have pervasive effects on how the Earth system functions, and it interacts with several other planetary boundaries. For example, loss of biodiversity can increase the vulnerability of terrestrial and aquatic ecosystems to changes in climate and ocean acidity, thus reducing the safe boundary levels of these processes.

From an Earth-system perspective, setting a boundary for biodiversity is difficult. Ideally, a planetary boundary should capture the role of biodiversity in regulating the resilience of systems on Earth.

Proposal: extinction rate is proposed as an indicator. Researchers suggested planetary boundary for biodiversity of **ten times the background rates of extinction**, which is only a very preliminary estimate. More research is required to pin down this boundary with greater certainty.

The global extinction rate far exceeds the rate of speciation, and consequently, loss of species is the primary driver of changes in global biodiversity.

3.Nitrogen and Phosphorus cycles

Modern agriculture is a major cause of environmental pollution, including large-scale nitrogen- and phosphorus-induced environmental change. On the planetary scale, the additional amounts of nitrogen and phosphorus activated by humans are now so large that they significantly perturb the global cycles of these two important elements.

- Nitrogen:

Human processes — primarily the manufacture of fertilizer for food production and the cultivation of leguminous crops — convert around 120 million tons of N_2 from the atmosphere per year into reactive forms — which is more than the combined effects from all Earth's terrestrial processes.

Researchers have defined the boundary by considering the human fixation of N_2 from the atmosphere as a giant 'valve' that controls a massive flow of new reactive nitrogen into Earth.

Proposal: researchers suggested that this valve should contain the flow of new reactive nitrogen to **35 million tons of nitrogen per year**.

- Phosphorous:

Phosphorus is a fossil mineral that accumulates because of geological processes. It is mined from rock and its uses range from fertilizers to toothpaste. Some 20 million tons of phosphorus are mined every year and around 8.5 million–9.5 million tons of it finds its way into the oceans.

Proposal: no more than **11 million tons of phosphorus per year** should be allowed to flow into the oceans.

In this article, researchers presented evidence that three boundaries have been overstepped and they did tentatively quantify seven boundaries, but some of the figures are merely their first best guesses.

The evidence so far suggested that, as long as the thresholds were not crossed, humanity had the freedom to pursue long-term social and economic development (Nature, 2009).

The table below was presented by the Ecology and Society journal of integrative science for resilience and sustainability. Click HERE to see the original table in bigger size.

Table 2. Proposed Planetary Boundaries

Earth System process	Control variable	Threshold avoided or influenced by slow variable	Planetary Boundary (zone of uncertainty)	State of knowledge*
Climate change	Atmospheric CO_2 concentration, ppm; Energy imbalance at Earth's surface, W m^{-2}	Loss of polar ice sheets. Regional climate disruptions. Loss of glacial freshwater supplies. Weakening of carbon sinks.	Atmospheric CO_2 concentration: 350 ppm (350-550 ppm) Energy imbalance:+1 W m^{-2} (+1.0 – +1.5 W m^{-2})	1. Ample scientific evidence. 2. Multiple sub-system thresholds. 3. Debate on position of boundary.
Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag})	Conversion of coral reefs to algal-dominated systems. Regional elimination of some aragonite- and high-magnesium calcite-forming marine biota Slow variable affecting marine carbon sink.	Sustain ≥ 80 % of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80 % - ≥70 %)	1. Geophysical processes well-known. 2. Threshold likely. 3. Boundary position uncertain due to unclear ecosystem response.
Stratospheric ozone depletion	Stratospheric O_3 concentration, DU	Severe and irreversible UV-B radiation effects on human health and ecosystems.	<5% reduction from pre-industrial level of 290 DU (5 - 10 %)	1. Ample scientific evidence. 2. T hreshold well established. 3. Boundary position implicitly agreed and respected .
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	Disruption of monsoon systems. Human health effects. Interacts with climate change and freshwater boundaries.	To be determined	1. Ample scientific evidence. 2. Global threshold behaviour unknown. 3. Unable to suggest boundary yet.
Biogeo-chemical flows: interference with P and N cycles	P: inflow of phosphorus to ocean, increase compared to natural background weathering N: amount of N_2 removed from atmosphere for human use, Mt N yr^{-1}	P: avoid a major oceanic anoxic event (including regional), with impacts on marine ecosystems. N: slow variable affecting overall resilience of ecosystems via acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems.	P: < 10× (10× - 100×) N: Limit industrial and agricultural fixation of N_2 to 35 Mt N yr^{-1}, which is ~ 25% of the total amount of N_2 fixed per annum naturally by terrestrial ecosystems (25- 35%)	P: (1) Limited knowledge on ecosystem responses; (2) High probability of threshold but timing is very uncertain; (3) Boundary position highly uncertain. N: (1) Some ecosystem responses known; (2) Acts as a slow variable, existence of global thresholds unknown; (3) Boundary position highly uncertain.
Global freshwater use	Consumptive blue water use, km^3 yr^{-1}	Could affect regional climate patterns (e.g., monsoon behaviour). Primarily slow variable affecting moisture feedback, biomass production, carbon uptake by terrestrial systems and reducing biodiversity	< 4,000 km^3 yr^{-1} (4,000 - 6,000 km^3 yr^{-1})	1. Scientific evidence of ecosystem response but incomplete and fragmented. 2. Slow variable, regional or subsystem thresholds exist. 3.. Proposed boundary value is a global aggregate, spatial distribution determines regional thresholds
Land system change	Percentage of global land cover converted to cropland	Trigger of irreversible & widespread conversion of biomes to undesired states. Primarily acts as a slow variable affecting carbon storage and resilience via changes in biodiversity and landscape heterogeneity	≤ 15% of global ice-free land surface converted to cropland (15 – 20%)	1. Ample scientific evidence of impacts of land cover change on ecosystems, largely local and regional. 2. Slow variable, global threshold unlikely but regional thresholds likely. 3. Boundary is a global aggregate with high uncertainty, regional distribution of land system change is critical.
Biodiversity loss	Extinction rate , extinctions per million species per year (E/MSY)	Slow variable affecting ecosystem functioning at continental and ocean basin scales. Impact on many other boundaries – C storage, freshwater, N and P cycles, land systems. Massive loss of biodiversity unacceptable for ethical reasons.	< 10 E/MSY (10 – 100 E/MSY)	1. Incomplete knowledge on the role of biodiversity for ecosystem functioning across scales. 2. Thresholds likely at local and regional scales 3. Boundary position highly uncertain.
Chemical pollution	For example, emissions, concentrations, or effects on ecosystem and Earth system functioning of persistent organic pollutants (POPs), plastics, endocrine disruptors, heavy metals, and nuclear wastet.	Thresholds leading to unacceptable impacts on human health and ecosystem functioning possible but largely unknown. May act as a slow variable undermining resilience and increase risk of crossing other threshold.	To be determined	1. Ample scientific evidence on individual chemicals but lacks an aggregate, global-level analysis. 2. Slow variable, large-scale thresholds unknown. 3. Unable to suggest boundary yet.

* State of knowledge regarding three factors: 1. Basic understanding of Earth system process. 2. Existence of threshold behaviour 3. Position of the boundary

Figure 3 - Proposed Planetary Boundaries. (Adapted from Ecology and Society, 2009).

In this journal (Ecology and Society, 2009), the other six PBs are explained:

4.Stratospheric Ozone Depletion

Stratospheric ozone filters ultraviolet radiation from the sun.

The appearance of the Antarctic ozone hole was an example of a threshold in the Earth System being crossed. A combination of increased concentrations of anthropogenic ozone-depleting substances (like chlorofluorocarbons) and polar stratospheric clouds moved the Antarctic stratosphere into a regime in which ozone disappeared in the lower stratosphere in the region during the Austral spring.

In the case of global, extra-polar stratospheric ozone, there is no clear threshold around which to construct a boundary. As such, the placement of the researchers` boundary in this case is more uncertain than, for example, in the case of ocean acidification. They considered the planetary boundary for ozone levels to be a <5% decrease in column ozone levels for any particular latitude with respect to 1964–1980 values (Chipperfield et al. 2006).

Fortunately, because of the actions taken because of the Montreal Protocol, we appear to be on a path that avoids transgression of this boundary.

DU - The Dobson Unit is the most common unit for measuring ozone concentration (NASA, n.d).

5.Ocean Acidification

Ocean acidification poses a challenge to marine biodiversity and the ability of oceans to continue to function as a sink of CO_2 (it removes roughly 25% of human emissions).

Addition of CO_2 to the oceans increases the acidity (lowers pH) of the surface seawater. Many marine organisms are very sensitive to changes in ocean CO_2 chemistry—especially those biotas that use carbonate ions dissolved in the seawater to form protective calcium carbonate shells or skeletal structures.

The rate of acidification is at least 100 times faster than at any other time in the last 20 million years.

Marine organisms secrete calcium carbonate primarily in the forms of aragonite (which is produced by corals, many mollusks, and other marine life) and calcite (which is produced by different single-celled plankton and other groups).

Globally, the surface ocean aragonite saturation state (Ω_{arag}) is declining with rising ocean acidity. It has fallen from a pre-industrial value of Ω_{arag} = 3.44 to a current value of 2.9.

Deleterious effects on many marine organisms start well above the geochemical threshold of Ω_{arag} = 1, with calcification rates for some organisms being reduced by 10%–60% for a doubling of atmospheric CO_2 (Guinotte and Fabry 2008, Fabry et al. 2008).

Ocean acidification may have serious impacts on coral reefs and associated ecosystems.

6. Global Freshwater use.

Estimates indicate that 90% of global green water flows are required to sustain critical ecosystem services (Rockström et al. 1999), whereas 20%–50% of the mean annual blue water flows in river basins are required to sustain aquatic ecosystem functioning (Smakhtin 2008).

Green water flows influence, at the regional scale, rainfall levels through moisture feedback and, thereby, the availability of blue water resources. Green water-induced thresholds include the collapse of biological sub-systems because of regional drying processes.

Based on the global assessments of impacts of global green and blue water use, researchers estimated that transgressing a boundary of ~4,000 $km^3 yr^{-1}$ of consumptive blue water use (with a zone of uncertainty of 4000–6000 $km^3 yr^{-1}$) will significantly increase the risk of approaching green and blue water-induced thresholds (collapse of terrestrial and aquatic ecosystems, major shifts in moisture feedback, and freshwater/ocean mixing) at regional to continental scales. Currently, withdrawals of blue water amount to ~4,000 $km^3 yr^{-1}$ (Oki and Kanae 2006) whereas consumptive use is ~2,600 $km^3 yr^{-1}$ (Shiklomanov and Rodda 2003).

In Handbook of Water Use and Conservation, by Amy Vickers, **water withdrawal is** defined as "water diverted or withdrawn from a surface water or groundwater source." **Consumptive water use**, on the other hand, **is** defined as "water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment.” (Water Footprint Calculator, 2022).

Blue water: Fresh surface and groundwater, in other words, the water in freshwater lakes, rivers and aquifers.

Green water: the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. Green water can be made productive for crop growth (although not all green water can be taken up by crops, because there will always be evaporation from the soil and because not all periods of the year or areas are suitable for crop growth) (Hoekstra et al. (2011)).

Green water use in rainfed agriculture, currently estimated at ~5000 $km^3\ yr^{-1}$, may have to increase by 50% by 2030 to ~7500 km^3/yr, to ensure food security (Rockström et al. 2007), whereas consumptive blue water use for irrigation may increase by 25%–50%, corresponding to 400–800 $km^3\ yr^{-1}$ by 2050 (Comprehensive Assessment of Water Management in Agriculture 2007). This indicates that the remaining safe operating space for water may be largely committed already to cover necessary human water demands in the future.

7. Land-System change.

Land-system change is driven primarily by agricultural expansion and intensification.

Conversion of forests and other ecosystems to agricultural land has occurred at an average rate of 0.8% yr^{-1} (per year) over the past 40–50 years and is the major global driver behind loss of ecosystem functioning and services (MEA 2005a).

As a planetary boundary, researchers proposed that no more than 15% of the global ice-free land surface should be converted to cropland. About 12% of the global land surface is currently under crop cultivation (Foley et al. 2005, Ramankutty et al. 2008). The allowed 3% expansion (approximately 400 Mha (Million Hectares)) to the level researchers proposed as a land-system boundary will most likely be reached over the coming decades and includes suitable land that is not either currently cultivated or is under forest cover—e.g., abandoned cropland in Europe, North America, and the former Soviet Union and some areas of Africa’s savannas and

South America’s cerrado.

8. Aerosol Loading.

Human activities since the pre-industrial era have doubled the global concentration of most aerosols (Tsigaridis et al. 2006).

Aerosols influence the Earth’s system.

From the perspective of human-health effects, fine particulate air pollution ($PM_{2.5}$) (The term fine particles, or particulate matter 2.5 (PM2.5), refers to tiny particles or droplets in the air that are two and one half microns or less in width) is responsible for about 3% of adult cardiopulmonary disease mortality, about 5% of tracheal, bronchial, and lung cancer mortality, and about 1% mortality from acute respiratory infection in children in urban areas worldwide (Cohen et al. 2005). These effects convert to about 800 000 premature deaths and an annual loss of 6.4 million life years, predominantly in developing Asian countries.

The same aerosol components (e.g., particulates, tropospheric ozone, oxides of sulphur and N) lead to other deleterious effects. Crop damage from exposure to ozone, forest degradation and loss of freshwater fish due to acidic precipitation, changes in global precipitation patterns and in energy balance are further examples of indirect effects of air pollution on human well-being.

The complexity of aerosols, in terms of the large variety of particles involved, with different sources, impacts, and spatial and temporal dynamics, makes it difficult to define a planetary boundary above which effects may cause unacceptable change. It is not yet possible to identify a safe boundary value for aerosol loading.

9. Chemical Pollution.

Primary types of chemical pollution include radioactive compounds, heavy metals, and a wide range of organic compounds of human origin (e.g., Plastics). Chemical pollution adversely affects human and ecosystem health.

Chemical pollution can influence the Earth System. Chemical pollution also interacts with the climate-change boundary through the release and global spread of mercury from coal burning and from the fact that most industrial chemicals are currently produced from petroleum, releasing CO_2 when they are degraded or incinerated as waste.

There are 80 000 to 100 000 chemicals on the global market (U.S. Environmental Protection Agency 1998, Commission of the European Communities 2001).

A chemical pollution boundary may require setting a range of sub-boundaries based on the effects of many individual chemicals combined with identifying specific effects on sensitive organisms. Furthermore, a chemical pollution boundary interacts with the planetary boundary for aerosols because many persistent pollutants are transported long distances on aerosol particles. Researchers concluded that it is not possible at this time to define these nor is it clear how to aggregate them into a comprehensive single planetary boundary.

In the Ecology and Society journal article from 2009, researchers attempted to quantify the temporal trajectory of seven of the proposed planetary boundaries from pre-industrial levels to the present. Click HERE to see the below figure n a bigger size.

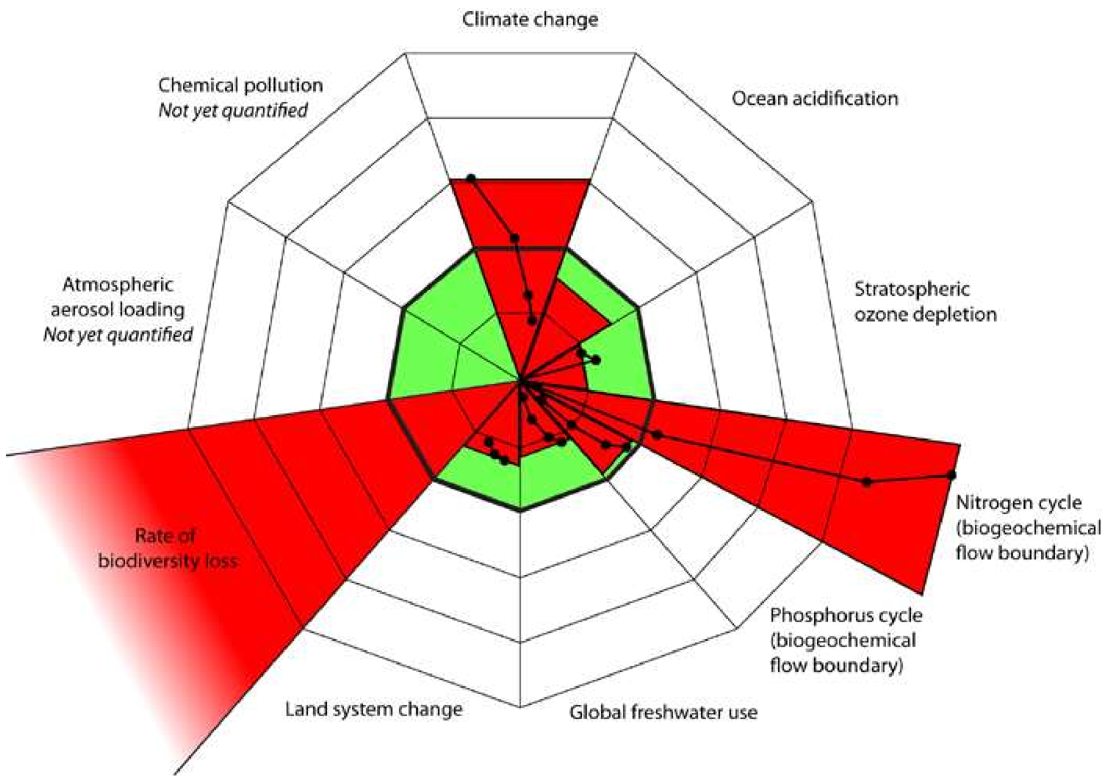

Figure 4 – Planetary boundaries already transgressed by 2009. (Rockström, J.,et al, 2009).

Planetary Boundaries 2015

In 2015, an international team of 18 researchers in the journal Science concluded that four of nine planetary boundaries were crossed because of human activity: extinction rate (one of two indicators for biosphere integrity), deforestation, atmospheric carbon dioxide (an indicator for climate change), and the flow of nitrogen and phosphorus. Action therefore needs to be taken to return to safe operating space in these processes (Steffen, W., et al., 2015).

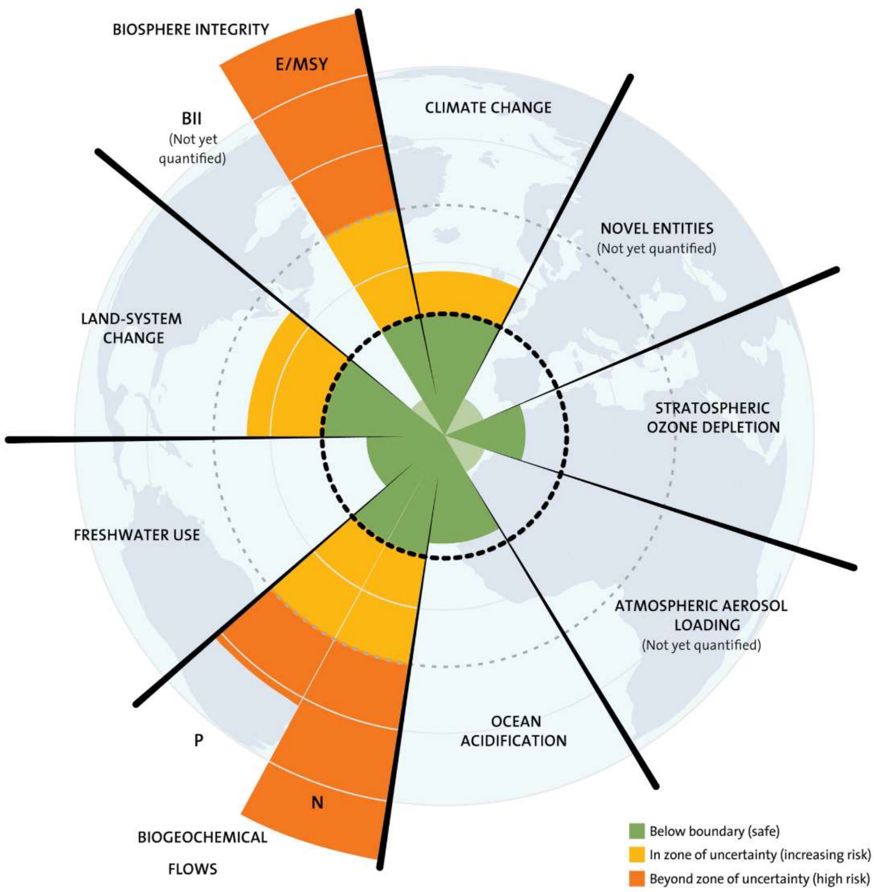

Figure 5 – Planetary Boundaries. (Stockholm Resilience Center). credit: J. Lokrantz/Azote based on Steffen et al. 2015)

Biosphere Integrity

- Extinction rate (**E/MSY**).

In an article published in Science journal in 2015, Ceballos, G., et al. assessed, using extremely conservative assumptions, whether human activities were causing a mass extinction. They used an estimate of a background rate of 2 mammal extinctions per 10,000 species per 100 years (that is, 2 E/MSY), which is twice as high as widely used previous estimates. They then compared this rate with the current rate of mammal and vertebrate extinctions at that time. The average rate of vertebrate species loss over the last century is up to 100 times higher than the background rate. Under the 2 E/MSY background rate, the number of species that have gone extinct in the last century would have taken, depending on the vertebrate taxon, between 800 and 10,000 years to disappear. These estimates reveal an exceptionally rapid loss of biodiversity over the last few centuries, indicating that a sixth mass extinction is already under way (Ceballos, G, et al., 2015).

- Biodiversity Intactness Index (**BII**).

It measures biodiversity change using abundance data on plants, fungi, and animals worldwide. The Index shows how local terrestrial biodiversity responds to human pressures such as land use change and intensification (Natural History Museum, n.d.).

Functional diversity refers to those components of biodiversity that influence how an ecosystem operates or functions. It is measured by the values and range in the values, for the species present in an ecosystem, of those organismal traits that influence one or more aspects of the functioning of an ecosystem. Functional diversity is of ecological importance because it, by definition, is the component of diversity that influences ecosystem dynamics, stability, productivity, nutrient balance, and other aspects of ecosystem functioning (Norman, W, 2013).

Land- System change.

The updated biosphere integrity boundary provides a considerable constraint on the amount and pattern of land-system change in all terrestrial biomes: forests, woodlands, savannas, grasslands, shrublands, tundra, and so on. The land-system change boundary is now focused more tightly on a specific constraint: the bio geophysical processes in land systems that directly regulate climate—exchange of energy, water, and momentum between the land surface and the atmosphere. The control variable has been changed from the amount of cropland to the amount of forest cover remaining, as the three major forest biomes—tropical, temperate, and boreal—play a stronger role in land surface–climate coupling than other biomes (Steffen, W, 2015).

Planetary Boundaries 2022

- Novel Entities – Chemical pollution

In January 2022, 14 scientists concluded in the scientific journal [Environmental Science and Technology](#) that **humanity has exceeded** a planetary boundary related to environmental pollutants and other "**novel entities**" including plastics.

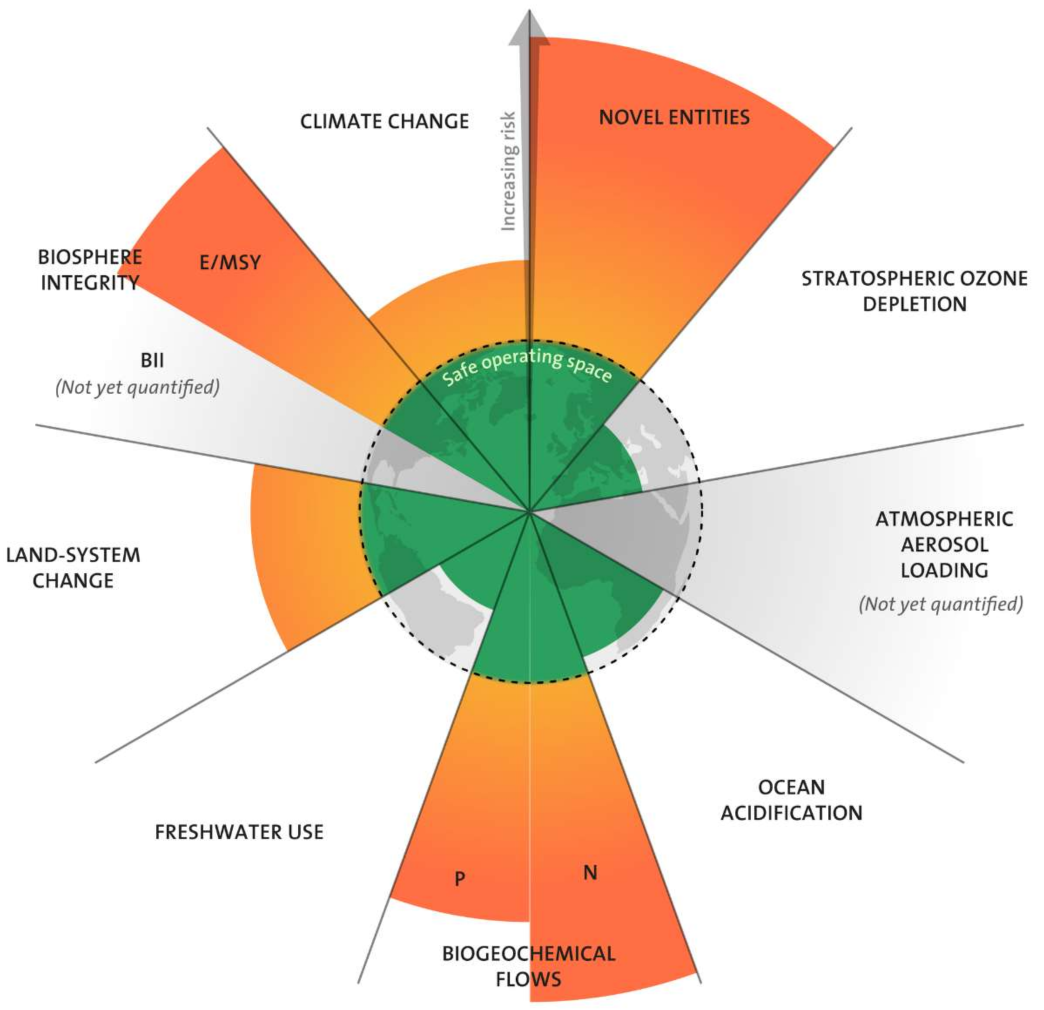

Figure 6 – Planetary Boundaries 2022. ([Stockholm Resilience center](#)). Credit: "Azote for Stockholm Resilience Centre, based on analysis in Persson et al 2022 and Steffen et al 2015".

Chemical pollution has the potential to cause severe ecosystem and human health problems at different scales, but also to alter vital Earth system processes on which human life depends. “Chemical pollution” was included as one of nine planetary boundaries, in response to this understanding. Steffen et al. renamed the “chemical pollution” boundary to “novel entities” (NE), defined as “new substances, new forms of existing substances and modified life forms”, including “chemicals and other new types of engineered materials or organisms not previously known to the Earth system as well as naturally occurring elements (for example, heavy metals) mobilized by anthropogenic activities”.

So far, no quantitative boundary has been defined for the novel entities’ boundary, although, some specific chemicals are quantified under other planetary boundaries, such as greenhouse gases and CFCs.

In this research the focus is on chemical pollution, highlighting **plastic pollution** as a particular subset issue of high concern, and providing an assessment of the current status of this planetary boundary. Researcher concluded that increasing trends of production and emissions of diverse novel entities that exceed the efforts at safety assessment and monitoring are a transgression of the planetary boundary and that immediate actions are needed to return us to the safe operating space.

After several decades of mass production, plastics are now ubiquitous across the planet.

In a historic resolution at the UN Environment Assembly on the 02nd March 2022, 175 nations agreed to develop a legally binding agreement on plastic pollution by 2024, prompting a major step towards reducing greenhouse gas emissions from plastic production, use and disposal (UNEP, 2022).

- Freshwater

In April 2022, a reassessment of the planetary boundary for freshwater indicates that it has now been **transgressed**. This conclusion is due to the inclusion of “**green water**” – the water available to plants - into the boundary assessment for the first time.

Green water is the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. Green water can be made productive for crop growth (although not all green water can be taken up by crops, because there will always be evaporation from the soil and because not all periods of the year or areas are suitable for crop growth) (Water Footprint Network, n.d).

The assessment, published in 2022 in the journal Nature Reviews Earth & Environment, is based on evidence of widespread changes in soil moisture relative to mid-Holocene and pre-industrial conditions and green-water driven destabilization of ecological, atmospheric, and biogeochemical processes.

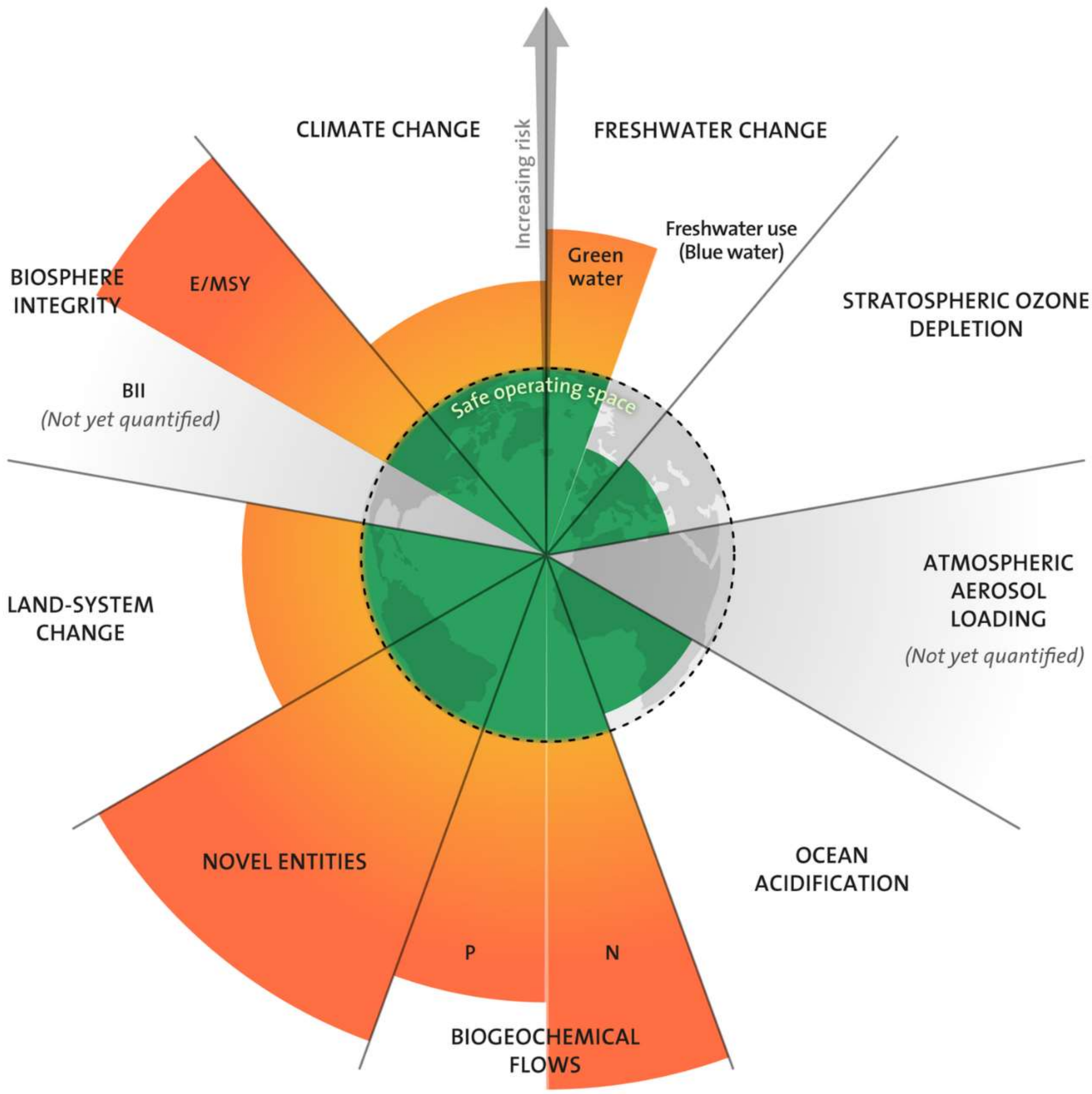

Figure 7 – Planetary Boundary Freshwater exceeded. (Stockholm Resilience center). Credit: "Azote for Stockholm Resilience Centre, based on analysis in Wang-Erlandsson et al 2022".

Conclusion

All the earth Systems are interconnected and exist in a delicate balance that has kept conditions in our planet relatively stable during the last 10.000 years. This stability helped humanity flourish. But as the population has grown, we have used more and more resources away from these life support systems, diverting water, land and minerals to agriculture, industry, and urban developments.

In 2007 Johan Rockström and Will Steffen set out to answer a fundamental question: What is the safe operating space for humanity on planet Earth? In other words, what are the limits of key Earth system processes that we cannot exceed if we want to avoid rapid and catastrophic environmental change? Working with an international team of scientists, they defined nine processes that keep Earth`s life support system stable. They also estimated the limits of how far we could change and exploit these processes before the system would pass a threshold of no-return. They suggested limits called Planetary Boundaries, guardrails to keep us a safe distance from these catastrophic tipping points.

In the 1980s scientists found that chemicals called Cloro-Fluoro-carbons (CFCs) were degrading the ozone layer, a thin atmospheric layer that absorbs some of the dangerous ultraviolet radiation from the sun, and acts like a protective layer of sunscreen for the planet. But CFCs were used all over the world in refrigerators, aerosol cans, and other products. Alarming satellite data revealed a dangerous thinning of ozone over the Antarctic. In response to this threat, the world`s nations met in 1987 and signed the Montreal Protocol on substances that deplete the ozone layer. They started phasing out CFCs. Today the ozone layer is in recovery, and it is hoped the damage to this vital life support system will be repaired by 2050. Humanity, for the first time, has stepped back from overshooting a planetary boundary.

In addition to the Ozone layer, Rockström and Steffen identified eight other planetary boundaries: Biogeochemical flows of Nitrogen and Phosphorous; Climate change; Ocean acidification; Freshwater consumption; Biodiversity; Land system change; Atmospheric aerosol pollution and Chemical pollution. These processes are interlinked. Passing a threshold in one area can lead to a cascade of changes, destabilizing other systems, causing them to topple like dominos beyond our control. For example, climate change (a planetary boundary) is triggered by increasing atmospheric carbon emissions, but that excess carbon also causes ocean acidification (another planetary boundary), which in turn impacts marine species like corals and fish, destabilizing biodiversity (another planetary boundary). Likewise, deforestation in huge tropical forests reduces the amount of water evaporating from leaves, which reduces rainfall, causes forests to fall into dry savannas and possibly altering weather systems across entire continents. In this case, land use change (another planetary boundary) helps generate climate change, which diminishes biodiversity, which brings more climate change.

Diverse ecosystems are essential to provide us with food, clean water, materials, medicine, even flood defenses. It is these ecosystem services that are vital to the human future.

Researchers estimate that humanity is already living outside the safe zone for six of the nine planetary boundaries, putting Earth on course for disruptive changes in our life support system not experienced for tens of thousands of years.

The concept of planetary boundaries was developed as a guide to help us to keep Earth conditions within a safe range. Now overshoot underlines the urgency of the sustainability crisis confronting us. But the first planetary boundary humanity crossed offers us a path ahead. If nations can come together, as they did with the Montreal Protocol to treat the ozone layer, then humanity can address the rest of the overshot planetary boundaries and there is a chance that we can reverse current trends and steer Earth`s life support systems back to the safe zone again.

References

- Ceballos, G., Ehrlich, P., Barnosky, A., Garcia, A., Pringle, R., & Palmer, T., (2015). *Accelerated modern human–induced species losses: Entering the sixth mass extinction.* Science Vol 1, No 5. https://doi.org/10.1126/sciadv.1400253

- Cohen, A. J., H. R. Anderson, B. Ostro, K. D. Pandey, M. Krzyzanowski, N. Künzli, K. Gutschmidt, A. Pope, I. Romieu, J. M. Samet, and K. Smith. 2005. The global burden of disease due to outdoor air pollution. Journal of Toxicology and Environmental Health, Part A 68:1301–1307.

- Comprehensive Assessment of Water Management in Agriculture. 2007. Water for food, water for life: a comprehensive assessment of water management in agriculture. Earthscan and International Water Management Institute, London, UK.

- Foley, J. A., R. DeFries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, III, M. T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. A. Howard, C. J. Kucharik, C. Monfreda, J. A. Patz, I. C. Prentice, N. Ramankutty, and P. K. Snyder. 2005. Global consequences of land use. Science 309:570–574.

- Guinotte, J. M., and V. J. Fabry. 2008. Ocean acidification and its potential effects on marine ecosystems. Annals of the New York Academy of Sciences 1134:320–342.

- Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M. (2011) – " *The Water Footprint Assessment Manual: Setting the Global Standard*", Earthscan, London, UK.

- Intergovernmental Panel on Climate Change (IPCC), (2007). AR4 Climate Change 2007: The Physical Science Basis. Chapter 2. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf

- Millenium Ecosystem Assessment (MEA), (2005). Ecosystems and human well-being. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

- Norman, W., Mouillot, D., (2013). Functional Diversity Measures. Sciencedirect. https://doi.org/10.1016/B978-0-12-384719-5.00356-7

- Oki, T., and S. Kanae. 2006. Global hydrological cycles and world water resources. Science 313:1068–1072.

- Persson, L., Almroth, B., Collins, C., Cornell, S., De Wit, C., Diamond, M., Fantke, P., et al. (2022). *Outside the Safe Operating Space of the Planetary Boundary for Novel Entities.* Environmental Science technology. https://pubs.acs.org/doi/10.1021/acs.est.1c04158#

- Ramankutty, N., A. T. Evan, C. Monfreda, and J. A. Foley. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochemical Cycles 22:GB1003. doi:10.1029/2007GB002952.

- Rockström, J., M. Falkenmark, and M. Lannerstad. 2007. Assessing the water challenge of a new green revolution in developing countries. Proceedings of the National Academy of Sciences 104:6253–6260.

- Rockström, J., Steffen, W., Noone, K. *et al. Planetary Boundaries: Exploring the Safe Operating Space for Humanity.* Ecology and Society VOL. 14, N0. 2, Art. 32 (2009). http://www.ecologyandsociety.org/vol14/iss2/art32/

- Rockström, J., Steffen, W., Noone, K. *et al.* A safe operating space for humanity. *Nature* 461, 472–475 (2009). https://doi.org/10.1038/461472a

- Shiklomanov, I. A., and J. C. Rodda. 2003. World water resources at the beginning of the 21st century. UNESCO and Cambridge University Press, Cambridge, UK.

- Smakhtin, V. 2008. Basin closure and environmental flow requirements. International Journal of Water Resources Development 24:227–233.

- Steffen, W., Richardson, K., Rockström, J., Cornell, S., Fetzer, I., Bennett, E., Biggs, R., et al. (2015). Planetary boundaries: Guiding human development on a changing planet. Science 347,1259855 (2015). https://doi.org/10.1126/science.1259855

- Stockholm Resilience center, (n.d.). Planetary Boundaries. https://www.stockholmresilience.org/planetary-boundaries

- Tsigaridis, K., M. Krol, F. J. Dentener, Y. Balkanski, J. Lathière, S. Metzger, D. A. Hauglustaine, and M. Kanakidou. 2006. Change in global aerosol composition since preindustrial times. Atmospheric Chemistry and Physics 6:5143–5162.

- U.S. Environmental Protection Agency. 1998. Chemical hazard data availability study: what do we really know about the safety of high production volume chemicals? Office of Pollution Prevention and Toxics, Washington, D.C., USA.

- United Nations Environment Programme (UNEP), (2022). Historic day in the campaign to beat plastic pollution: Nations commit to develop a legally binding agreement. https://www.unep.org/news-and-stories/press-release/historic-day-campaign-beat-plastic-pollution-nations-commit-develop

- Wang- Erlandsson, L., Tobian, A., Van der Ent, R., Fetzer, I., Wierik, S., Porkka, M., Staal, A., et al. (2022). A planetary boundary for green water. Nature, Vol.3. https://www.nature.com/articles/s43017-022-00287-8.epdf?sharing_token=hier2n7O_tPClC8-r06bmdRgN0jAjWel9jnR3ZoTv0P2KmS6Qajbkp2nZuUVCQ0Vp_P0L_fySeHB

sRgAquqyIOp9LnWtWwctu_gtf2IN3rQca4cpkK1yn9HaZMp0U7_CeAUSZHD1Xu5KL__3KimuwqoA5hdvBx21Dt1POSVkJdo%3D

Videos to watch.

TED TALKS (by Johan Rockström):

2010 - Let the environment guide our development: https://youtu.be/RgqtrlixYR4

2021 - 10 years to transform the future of humanity -- or destabilize the planet | Johan Rockström: https://youtu.be/8SI28fkrozE

ELLEN MACARTHUR FOUNDATION:

2022 - How many planetary boundaries have already been crossed? | The Circular Economy Show: https://youtu.be/9SVYnKKOG-w

MASTER CLASS ON CLIMATE CRISIS:

2023 - Johan Rockström: A safe and just future within Planetary Boundaries: https://youtu.be/OGNXBAvGBH0

NETFLIX MOVIE:

2020- Breaking Boundaries: The Science of Our Planet | Official Trailer | Netflix: https://youtu.be/Gb6wQtNjblk