Planetary Health Check Report – 2024 Supplement

1. More detailed Figure and Table captions of main Planetary Health Check report

1.1 Figures

Figure 4: Evolution of the global mean temperature over the last 500,000 years and projections until 2100 compared to past and projected human population size. Left and middle panels: Global mean temperature anomaly relative to the last millennium, estimated from Antarctic ice-core data. The reconstructed Antarctic temperature anomalies (Jouzel et al., 2007) were re-scaled by a factor of 0.5 following (Masson-Delmotte et al., 2010). The left panel shows the temperatures in the original temporal resolution (gray line) and averaged over the 1000 years (black line). Right panel: Observation-based global mean surface temperature anomalies from the HadCRUT data set (Climatic Research Unit (University of East Anglia), 2024); Morice et al., 2021; and Osborn & Jones, 2014, black line). Also shown is the expected temperature evolution for the IPCC Sixth Assessment Report Shared Socioeconomic Pathway (SSP) scenarios (Fyfe et al., 2024; Intergovernmental Panel on Climate Change (IPCC), 2023): SSP1-2.6 (blue), SSP2-4.5 (yellow) and SSP3-7.0 (red). Thick lines show the median estimates and thin lines show the lower and upper estimates (5%-95%) of the respective scenarios. The temperature anomalies are relative to the 1850-1900 average temperature. Estimate of the global population from 130,000 BCE to 2021 (lower light blue to red thick line) and population projections until 2100 (continuation of the line after 2021). The Holocene population estimates are from Ritchie et al., 2024. The population estimate of 325,000 in 130,000 BCE is from Sjödin et al., 2012. The straight thick line shows the median UN population projection (United Nations, Department of Economic and Social Affairs, Population Division, 2022) and the range shows the corresponding upper and lower 95% estimates.

Figure 23: Global Risk Map of the Biogeochemical Cycles Boundary Transgression - Phosphorus Cycle. The regional boundary status is calculated based on agricultural phosphorus fertilizer use in 2013 (Lu & Tian, 2017) and estimates of regional surplus boundaries.. Values range from within the Safe Operating Space (green) to the Zone of Increasing Risk (orange), and extend into the High Risk Zone (red/purple). The regional boundaries were preliminarily derived from the global boundaries, assuming a uniform rate of fertilizer application on cropland as proposed in Steffen et al., 2015. This results in a PB value of 4.1 kgP ha-1 yr-1 and a high risk value of 7.5 kgP ha-1 yr-1. Regional pollution limits may deviate significantly from these boundaries.

Figure 24: Rising Phosphorus Inputs for Agriculture. This graph shows the mean global phosphorus use
rate on all croplands in g P m^{-2} cropland $year^{-1}$, e.g., grams of phosphorus per square meter of cropland per
year from 1961 to 2013. Data from Lu & Tian, 2017. The time series starts in 1961. It is important to note that this measure is not weighted by cropland area, but by the area of the

regarded grid cells, so it does not directly relate to the global control variable of phosphorus flow from freshwater systems into the ocean.

Figure 25: Global Map of Change in Phosphorus Use Rate for Agriculture. The total difference of phosphorus use rates (in g P m^{-2} cropland year $^{-1}$, e.g., grams of phosphorus per square meter of cropland per year) calculated as the difference between the rates during the period 2009-2013 (last 5 years of data set) and the period 1961-1965 (first 5 years of data set). Shades of red indicate an increase in phosphorus use, while shades of blue indicate a decrease. The color bar is capped at ±3 to emphasize differences within this range. Approximately 4.4% of land grid cells show increases exceeding +3 grams of phosphorus per square meter cropland per year. Data from Lu & Tian, 2017.

Figure 26: **Global Risk Map of the Biogeochemical Cycles Boundary Transgression - Nitrogen Cycle**. The preliminary regional boundary status is calculated based on agricultural nitrogen surplus in the year 2010 and estimates of regional surplus boundaries based on thresholds for eutrophication of terrestrial and aquatic ecosystems and nitrate in groundwater. The assessment aligns with the suggestion for an enhanced control variable definition that is more closely related to nitrogen losses to the environment (nitrogen surplus defined as total nitrogen input from fertilizers, manure, biological fixation, and deposition minus the nitrogen removed by crops or grass, instead of the current control variable based on industrial and intentional fixation of nitrogen). Values range from within the Safe Operating Space (green; no exceedance of regional surplus boundaries) to the Zone of Increasing Risk (orange), and extend to the High Risk Zone (red/purple). Gray areas are non-agricultural areas. Note that the threshold between the Zone of Increasing Risk and the High Risk Zone is a preliminary estimate (20 kgN ha-1 yr-1) and needs further refinement. Based on data from (Schulte-Uebbing et al., 2022). Values of boundary transgression from within the safe operating space (green) over the zone of increasing risk/uncertainty (orange) to the high risk zone (red/purple). Based on the nitrogen surplus data for 2010 (Schulte-Uebbing et al., 2022).

Figure 27: Rising Nitrogen Inputs for Agriculture. This graph shows the mean global nitrogen use rate on all croplands in g N m^{-2} cropland year $^{-1}$, e.g., grams of nitrogen per square meter of cropland per year from 1961 to 2013. Data from Lu & Tian, 2017. The time series starts in 1961. It is important to note that this measure is not weighted by cropland area, but by the area of the regarded grid cells, so it does not directly relate to the control variable of industrial and intentional nitrogen fixation.

Figure 28: Global Map of Change in Nitrogen Use Rate for Agriculture Cycle. The total difference of nitrogen use rates (in g N m^{-2} cropland year^{-1}, e.g. grams of nitrogen per square meter cropland per year) calculated as the difference between the rates during the period 2009-2013 (last 5 years of data set) and the period 1961-1965 (first 5 years of data set). The color bar is capped at ±15 to emphasize differences within this range. Approximately 4.5% of land grid cells show increases exceeding +15 grams of nitrogen per square meter cropland per year. Data from Lu & Tian, 2017.

2. Supplementary Figures & Tables

2.1 Supplementary Tables

Supplementary Table 1: PB Interconnections and Drivers of transgression

Interactions					
Driver	**Affected PB**	**Process**	**Impact on PB**	**Relative importance**	**Literature**
Ocean Acidification (OA)	BI	Increased degradation of coral reefs can lead to collapse of marine food webs.	(-)	medium	Hoegh-Guldberg et al. 2017; Doney et al. 2009
	BI	increased OA can lead to a reduction in calcifying species and to the loss of habitat forming species	(-)	medium	Doney et al. 2009; Teixidó et al. 2024
	BI	Increased pCO2 can lead to increased photosynthesis rates	(+)	low	Das and Mangwani 2015
	AL	Decreasing pH can increases the potential for high dimethyl sulfides emissions by phytoplankton	(-)	low	Das and Mangwani 2015, Deng et al. 2021, Fung et al. 2022
	BI/BC	OA can lead to changes in nitrification and nitrogen fixation	(-/+)	low	Shi et al. 2012, Wannicke et al. 2018
	CC	OA can decrease the capacity of organisms to form carbonate shells, which allows oceans to absorb more CO2	(+)	low	Lade et al. 2019
	NE	Ocean acidification can alter the chemical behavior of pollutants, such as heavy metals	?	low	Jin et al. 2021
Freshwater Change (FW)	BI	Changes in streamflow (e.g. by dams) can causes habitat destruction	(-)	low	Gleeson et al. 2020, Broadley et al. 2022
	BI	Changes in streamflow and soil moisture alter transport and availability of nutrients	(-/+)	low	Gleeson et al. 2020, Lie et al. 2024
	BI	reduction in river flow/drain aquifers can lead to salinization and decrease productivity	(-)	low	Lade et al. SM, Broadley et al. 2022
	CC	Soil moisture, surface water and frozen water can alter earth surface albedo	(-)	low	Maina et al. 2022,
	BC	Changes in streamflow and soil moisture alter transport of nutrients	(-/+)	low	Gleeson et al. 2020, Lie et al. 2024
	LSC	Reduction of soil moisture/green water flow can lead to desertification/land degradation	(-)	high	AbdelRahman 2023

Biosphere Integrity (BI)	CC	Loss of biodiversity and ecosystem degradation can reduce the capacity for carbon uptake	(-)	high	Bustamante et al. 2015, Lade et al. 2020, Poorter et al. 2015, Cardinale et al. 2012
	CC	Increased productivity due to increased eutrophication can lead to increased GHG (Methane) emissions	(-)	medium	Beaulieu et al. 2019, Lade et al,. 2020, Rocher-Ros et al. 2023
	CC	Reduced biodiversity leads to a reduction of CO2 uptake in oceans	(-)	medium	Gruber et al. 2023, Lade et al. 2020, Nash et al. 2017
	BC	Biodiversity loss can alter nutrient cycles and lead to nutrients being added to ecosystems	(-/+)	low	Cui et al. 2022
	LSC	Degraded biosphere integrity can increase the vulnerability of forests to shocks or pests	(-)	high	Bustamante et al. 2015, Poorter et al. 2015
	FW	Loss of ecosystem functions reduce the capability to regulate the hydrological cycle that can lead to changes in water availability and quality	(-)	medium	Harrison et al. 2014
	OA	Decline in coral reefs and phytoplankton can exacerbate ocean acidification	(-)	low	Cornwall et al. 2021, Zhang et al. 2023
	NE	The capacity of ecosystems to degrade and assimilate pollutants is reduced leading to higher concentrations of harmful substances	(-)	low	Ferreira et al 2023
Stratospheric Ozone depletion (SO)	CC	Reduced absorption of UV in the stratosphere increases the UV radiation at Earth's surface	(-)	low	Lade et al. 2019
	BI	Reduced absorption of UV in the stratosphere increases UV radiation at Earth's surface with the potential to damage DNA and impair photosynthesis	(-)	low	Lade et al, EEPA 2019
	AL	Changes in UV radiation can influence the production of aerosols through chemical reactions in the atmosphere.	(-/+)	low	Lade et al. 2019
Biogeochemical Flows (BC)	BI	Nutrient runoff can degrade soil by increased acidification, eutrophication and simplification of ecosystems	(-)	low	Lade et al. 2019
	BI	Nutrient runoff from agricultural application into freshwater can lead to algal blooms, dead zones, loss of fish	(-)	medium	Lade et al. 2019
	BI	Nutrient runoff into the ocean can lead to large scale ocean hypoxic events, having strong impacts on the ocean ecosystems	(-)	low	Lade et al. 2019, Rockström et al. 2009

	LSC	Excessive use of fertilizers can lead to soil degradation (farmland)	(-)	medium	Lade et al. 2019
	FW	Nutrient runoff from agriculture, sewage and industrial processes can degrade freshwater quality	(-)	medium	du Plessis 2022
	AL	Nitrogen compounds, particularly ammonia (NH_3) from agriculture, can contribute to the formation of fine particulate matter ($PM_{2.5}$) in the atmosphere.	(-)	medium	Lade et al. 2019, Gu et al. 2021
	SO	Application of N fertilizers can lead to N_2O emissions that depletes ozone in the stratosphere	(-)	low	Lade et al. 2019, Campbel et al. 2017
Land system change (LSC)	CC	Deforestation and land conversion can reduce the capacity of these systems to absorb CO_2, contributing to higher atmospheric CO_2	(-)	high	Lade et al. 2020
	CC	Changes in land cover can alter the surface albedo. This affects the radiative forcing	(+)	high	Gibbard et al. 2005, Andrews et al. 2016
	BI	Land conversion can lead to habitat loss. Fragmentation of habitats can isolate populations, reducing genetic diversity	(-)	high	Lade et al. 2020, Lade et al. 2019, Campbell et al. 2017, Alkemade et al. 2009
	BI	Forest cover loss can lead to decreased water quality, altered flows etc. reducing species diversity	(-)	low	Semenchuk et al. 2022
	BI	Land system change can disrupt ecosystem services such as pollination, water purification, soil stabilization	(-)	medium	Bennet et al. 2020,du Plessis 2022, Delelegn et al. 2017, Borelli et al. 2020
	FW	Land system change can increase river discharge	(+)	low/medium	Lade et al. 2020
	FW	Deforestation can impact the hydrological cycle by reducing evapotranspiration and subsequent drying of the atmosphere	(-)	medium	Xu et al. 2022
	AL	Forest fires (associated with land clearing), as well as cleared agricultural land emit large amounts of aerosol	(-)	medium	Lade et al. 2020
Aerosol Loading (AL)	CC	Sulfate aerosols reflect sunlight, cooling the Earth's surface; Black carbon absorbs sunlight, warming the atmosphere	(-/+)	medium	IPCC AR5, Chapter 7 Clouds and Aerosols, Quaas et al. 2022
	CC	Aerosols act as cloud condensation nuclei, influencing cloud formation, properties and lifetimes. This can affect the energy balance as well as the hydrological cycle and climate dynamics	(-/+)	medium	IPCC AR5, Chapter 7 Clouds and Aerosols

	BC	changes of bioaerosols in the atmosphere can lead to changes in nutrient deposition	?	low	Kanakindou et al. 2018, Fröhlich-Nowoisky et al. 2016
	BC	Acidic rains can lead to soil acidification	(-)	low	Grennfelt et al. 2020
	OA	Some aerosols (e.g. those containing sulfur compounds) can increase acidic rain. When entering the ocean, this can increase its acidification	(-)	low	Doney et al. 2009
	BI	Aerosol deposition can deliver nutrients like iron, stimulating net primary production	(+)	?	Lade et al. 2020
	SO	Aerosols in the stratosphere can provide surfaces for heterogenous chemical reactions that can contribute to ozone depletion	(-)	low	Solomon et al. 1987
	SO	Aerosols can absorb UV radiation therefore increasing the safe level of ozone depletion	(+)	low	Lade et al. 2020
	BI	Increase release of pesticides, industrial chemicals and heavy metals can intoxicate a wide range of organisms; leading diversity loss and disruption of ecosystem services	(-)	high	Sigmund et al. 2023
	BI	The release of genetically modified organisms can lead to genetic pollution, affecting genetic diversity	(-)	low	Tsatsakis et al. 2017
	FW	Increased release of pharmaceuticals, personal care products and industrial chemicals can contaminate freshwater systems	(-)	medium	Richmond et al. 2017
	OA	Abiotic plastic degradation can induce a decrease in seawater pH	(-)	low	Romera-Castilla et al. 2023
	AL	The release of volatile organic compounds and persistent organic pollutants can contribute to the formation of secondary aerosols	(-)	high	Nault et al. 2021
Climate Change (CC)	BI	Rising temperatures and shifting precipitation patterns lead to changing weather regimes that can affect biological events such as habitat loss, species extinction, migration and the introduction of invasive species	(-)	high	Lade et al. 2020, Jaureguiberry et al. 2022
	BI	Extreme events and rising sea levels can lead to the salinisation of freshwater ecosystems	(-)	medium	Lade et al. 2020
	BC	Increases in extreme precipitation events can lead to an increase of agricultural runoff	(-)	low	Skidmore et al. 2023

	LSC	Climate stress on forests (e.g. increased frequency of wildfires and droughts) can lead to deforestation and land degradation	(-)	high	Flore et al. 2024
	FW	Changes in precipitation patterns and the melting of glaciers can impact freshwater availability.	(-/+)	medium	Konapala et al. 2020, Haeberli et al. 2020
	FW	Precipitation patterns can change due to climate change	(-/+)	high	Lade et al. 2020
	OA	Increasing CO2 levels lead to an increased absorption of CO2 in the oceans, exacerbating ocean acidification	(-)	high	Doney et al. 2009
	OA	Increasing temperatures can reduce the solubility of CO2 in water	(+)	low	Lade et al. 2020
	AL	Increased droughts and changing atmospheric circulations can increase dust formation and distribution	(-)	low	Zhao et al. 2019
	SO	Climate change reduces stratospheric temperatures due to heat being trapped at lower levels of the atmosphere, slowing ozone depleting chemical reactions and increasing the destruction of nitrous oxides	(+)	low	Lade et al. 2019
	NE	Increasing temperatures can enhance the volatility of chemical pollutants, altering their atmospheric concentration	(-)	low	Balbus et al. 2013, Bolan et al. 2023