Planetary boundaries, exceedances and potentials with a plant-based food system

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1. Introduction

In 2009 [1] and 2015 [2], the Stockholm Resilience Center identified a total of 9 anthropogenic planetary boundaries (PG) that must not be exceeded. A permanent exceeding of these Planetary Boundaries destabilizes the Earth system and endangers the existence of mankind. Four planetary boundaries have already been exceeded, two of them to such an extent that there is a secured high risk of catastrophic consequences for them (PG: loss of biodiversity, PG: emissions of eutrophic substances).

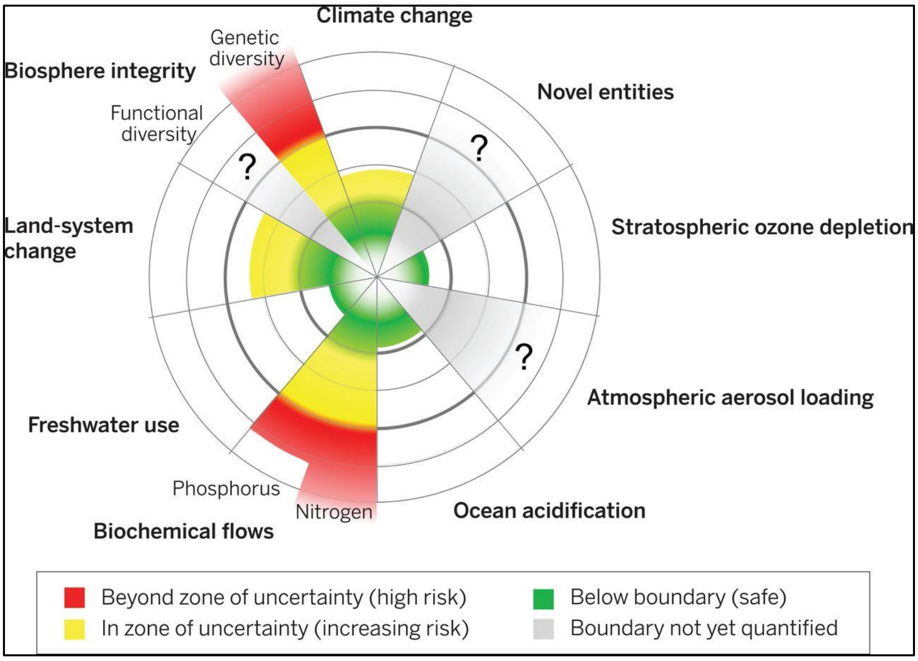

Figure 1: Nine Planetary Boundaries according to Stockholm Resilience Center 2015

Two of the four Planetary Boundaries each independently have the potential to make the Earth uninhabitable for humans (PG: loss of biodiversity, PG: climate change).

The four currently exceeded Planetary Boundaries are examined in more detail here, particularly with regard to potentials for a switch to a plant-based food system.

2. The four exceeded planetary boundaries and their interactions

Four Planetary Boundaries (PG) have been exceeded, two of them strongly (red area). Two Planetary Boundaries each individually have the potential to make the Earth uninhabitable for humans (red area). The Planetary Boundaries interact with each other. In addition, there are other factors such as acidifying gases, pesticides, and wildlife trade [3].

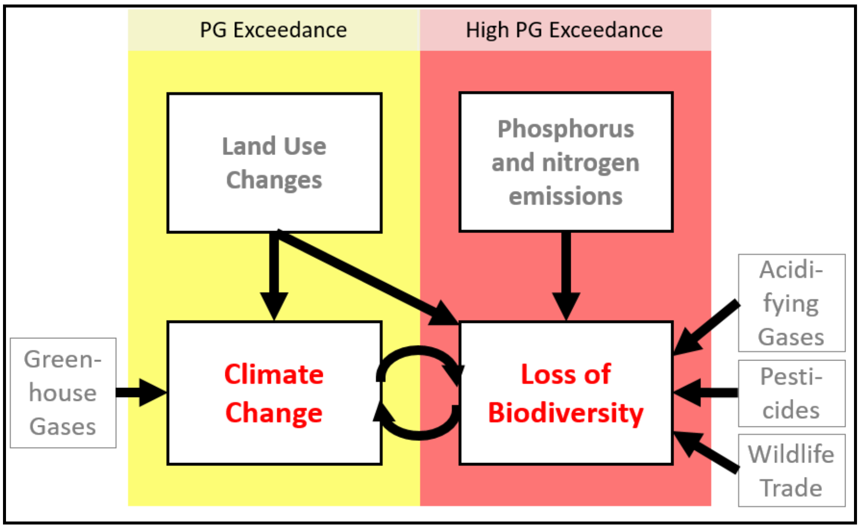

Figure 2: Overview of the four exceeded planetary boundaries, their interactions and additional influencing factors

2.1 Planetary Boundary: Land Use Changes

Land use change is primarily past and current land clearing and the primary cause of species extinction, biodiversity loss, and climate change due to a lack of carbon sinks. The metric for this planetary boundary is forest cover [1][2].

Metric: forest cover

Pre-industrial value (1750 AD): 90% [4].

Planetary boundary: 75% [2]

Forest cover 2015 according to [2]: 62%.

Calculations

Total global deforestation		
Forest cover 10k a bp [4]	60	m. km^2
Forest cover 1750 [4]	54	m. km^2
Forest cover 2019 [5]	39	m. km^2
Deforestation	21	m. km^2
Forest cover (39 M. km^2 / 60 M. km^2)	65%	

Table 1: Calculation of the current forest cover for 2019

The forest stand (2019) according to the calculation in Table 1 is 65%.

Global clearing for animal agriculture				
	Cropland	Pastures	Total	
Rainforest [6]	98	427	525	m. ha
Temperate forest [6]	194	220	414	m. ha
Boreal forest [6]	9	15	24	m. ha
Total (ha)	301	662	963	m. ha
Total (km^2)			9,6	m. km^2

Table 2: Calculation of global clearings for animal agriculture

The globally cleared areas for animal agriculture according to calculation in Table 2 amount to 9.6 million km2 (~46% : 9.6 million km2 / 21 million km2).

Switching to a plant-based food system could free up to 31 million km2 [7]. If prioritized appropriately, it is assumed here that the full 9.6 million km2 of land cleared for animal agriculture could be reforested for this purpose.

Result

A global shift to a plant-based food system will allow forest cover to increase from 65% to as much as 81% ((9.6 m. km^2 + 39 m. km^2)/ 60 m. km^2).

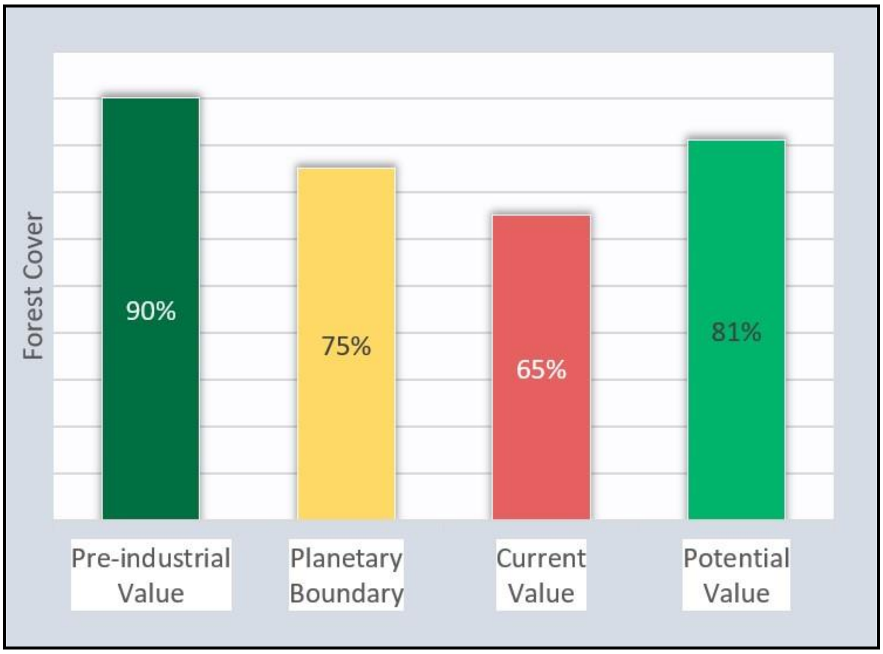

Figure 3: Potential reach of a forest stand when switching to a plant-based food system and reforestation

2.2 Planetary Boundary: Eutrophying emissions

Eutrophying substances are mainly nitrogen (N) and phosphorus (P). The application of manure and the use of artificial fertilizers result in an oversupply of bound nitrogen and phosphorus in the soil, which causes eutrophication of waters, rivers and eventually marine areas. Anthropogenic nitrogen fixation occurs through the production of artificial fertilizers (80 Mt/yr), the cultivation of legumes (40 Mt/yr), and the burning of fossil fuels (20 Mt/yr) and biomass (10 Mt/yr) [9].

Phosphorus is obtained via phosphate mining.

a1.) Global phosphorus fluxes

Measured variable: phosphorus inputs (P) to water bodies

Pre-industrial value (1750 AD): 1 Mt/Jr [1].

Planetary limit: 11 Mt/yr [2]

Global P fluxes 2015: 22 Mt/Jr (+100%) [2]

a2.) Phosphorus application regionally

Measured by phosphorus mining and application (P) to land.

Pre-industrial value (1750 AD): 0 Mt/yr.

Planetary boundary: 6.2 Mt/yr [2].

Regional P inputs in 2015: 14.2 Mt/Jr (+129%) [2].

b.) Nitrogen

Measured variable: anthropogenic nitrogen fixations.

Pre-industrial value (1750 AD): 0 Mt/yr [1].

Planetary boundary global anthropogenic N fixes: 62 Mt/Jr [2]

Global anthropogenic N fixations 2015: 150 Mt/Jr (+142%) [2]

Calculations

Share of biomass production for food		
Biomass of plants for people [10]	33	Exajoule
Biomass of animal feed [10]	130	Exajoule
Biomass for industry [10]	9	Exajoule
Biomass for bioenergy [10]	8	Exajoule
Biomass waste [10]	12	Exajoule
Share of biomass production for food (163 EJ/ 192 EJ)	85%	

Table 3: Calculation of share of biomass production for food

Reduction potential of global phosphorus fluxes		
Global P fluxes [2]	22	Mt/yr
Share of biomass production for food	85%	
P fluxes (food production)[1]	18,7	Mt/yr
Reduction potential (food production) in % [7]	49%	
Reduction potential (food production)	9,1	Mt/yr
Potentially achievable global P fluxes	12,9	Mt/yr

Table 4: Calculation of reduction potential of global phosphorus fluxes

Reduction potential of regional phosphorus application		
Regional P application to fields [2]	14,2	Mt/yr
Reduction potential in % [7]	49%	
Reduction potential	7	Mt/yr
Potentially achievable regional P applications	7,2	Mt/yr

Table 5: Calculation of reduction potential of regional phosphorus applications

[1] Phosphorus from phosphate mining is used to a total of 95% in agriculture. Parts of the global phosphorus fluxes also arise independently of anthropogenic phosphate mining through slurry/manure from animal agriculture. Overall, negligible inputs from non-agricultural sectors (detergents, industry, etc.) are therefore assumed here.

Reduction potential of nitrogen fixations		
Nitrogen fixations agriculture [9]	120	Mt/yr
Nitrogen fixations other sectors [9]	30	Mt/yr
Reduction potential of agricultural nitrogen fixations in % [7].	49%	
Reduction potential	59	Mt/yr
Potentially achievable nitrogen fixations	91	Mt/yr

Table 6: Calculation of reduction potential of nitrogen fixations

Results

A global shift to a plant-based food system will enable a reduction in anthropogenic nitrogen fixation from 150 Mt/yr to 91 Mt/yr, a reduction in global phosphorus inputs to water bodies from 22 Mt/yr to 13 Mt/yr, and a reduction in regional phosphorus application from 14 Mt/yr to 7 Mt/yr.

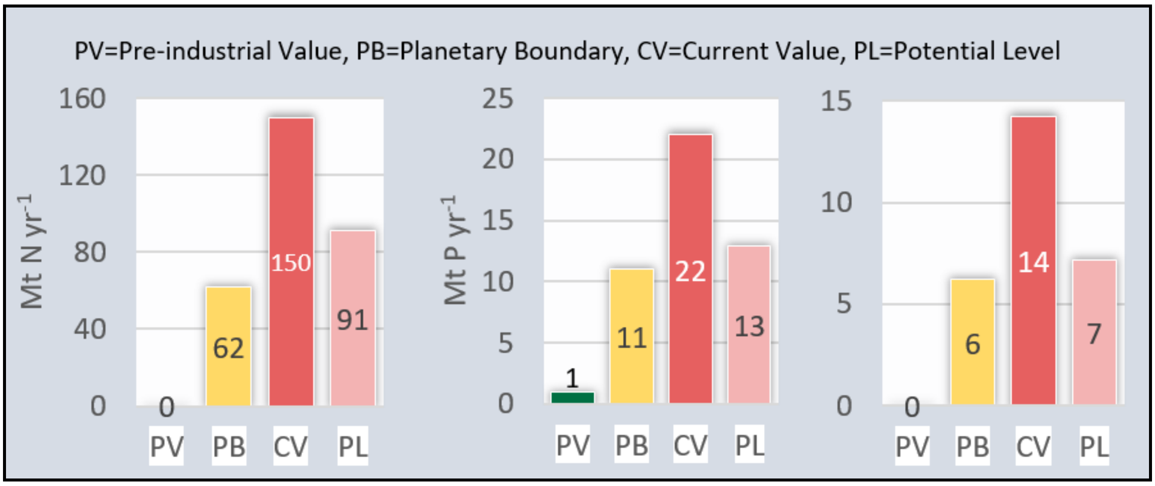

Figure 4: Potential achievability of nitrogen and phosphorus production and emissions with a shift to a plant-based food system

2.3 Planetary Boundary: Climate Change

Exceeding the Planetary Boundary for climate change alone can make the Earth uninhabitable for humans. The metrics for the Planetary Boundary are atmospheric CO2 concentration and anthropogenic radiative forcing of greenhouse gases and albedo effects. The relevant sectors for greenhouse gas emissions and radiative forcing are animal agriculture, fossil fuel power generation, fossil fuel transportation, fossil fuel heat generation, and cement production ([11], p.6).

a.) Anthropogenic increase of greenhouse gas CO_2

Measured variable: CO_2 concentration in the atmosphere

Pre-industrial value (1750 AD): 278 ppm

Planetary boundary: 350 ppm for CO_2 [2].

CO_2 concentration in 2021: 413 ppm [12].

b.) Anthropogenic increase in radiative forcing of all anthropogenic greenhouse gases, aerosols, and albedo effects.

Measured variable: radiative forcing

Pre-industrial value (1750 AD): 0 W/m^2.

Planetary boundary: 1 W/m^2 [2]

Radiative forcing 2021: 2.73 W/m^2 ([11], p.6, [12]) (+173%).

Calculations

a.) Anthropogenic increase of greenhouse gas CO_2

Number of years of necessary CO_2 sequestration for 350 ppm CO_2 including immediate stop of CO_2 emissions		
Necessary reduction of CO2 in the atmosphere in ppm [2]: 413 -350	63	ppm
Necessary reduction of CO2 in the atmosphere in in Gt ([11], p9): (5,135 x 10^6 Gt x (413–350) x 10^{-6} x (44,009 x $28,966^{-1}$))	491	Gt
Average additional sequestration per year on land due to CO2 fertilization, and in the ocean due to partial pressure [15]	18.6	Gt
Average sequestration per year with a plant-based food system and reforestation according to [13].	8.1	Gt
Average maximum sequestration per year with a plant-based food system and reforestation according to [8]	18.2	Gt
Number of years acc. [13] (491 Gt CO_2 / (18,6 Gt CO_2 + 8,1 Gt CO_2) [15][13]	~18	Years
Number of years acc. [8] (491 Gt CO_2 / (18,6 Gt CO_2 + 18,2 Gt CO_2) [15][8]	~13	Years

Table 7: Calculation of number of years of CO_2 sequestration for 350 ppm CO_2

b.) Radiative forcing

If all anthropogenic greenhouse gas emissions are stopped, the radiative forcings for most greenhouse gases decrease to zero after a few years (anthropogenic fractions of CH_4, O_3, H_2O, aerosols) because of the short lifetimes. Similarly, radiative forcings for contrails and anthropogenic albedo effects drop to (near) zero. N_2O and some CFCs/HFCs/HFs are long-lived greenhouse gases. For N_2O with a lifetime of 121 years, ~70% of the anthropogenic amount is still in the atmosphere after about 50 years. CFCs/HFCs/HFs have very different lifetimes, those with a high greenhouse effect and high concentrations (e.g., CFC-12) have a decay time of ~100 years [14]. On average, these greenhouse gases are assumed to have a remaining radiative forcing of about 50% after 50 years.

Necessary target level of CO_2 in the atmosphere in ppm to achieve a radiative forcing of 1 W/m^2 of all anthropogenic greenhouse gases		
Remaining radiative forcing of N_2O after 50 years (0.21 W/m^2 x 70%) [14]	0.14	W/m^2
Remaining radiative forcing of CFCs/HFCs/HFs after 50 years (0.36 W/m^2 x 50%) [14]	0.18	W/m^2
Necessary target level of radiative forcing of CO_2 (1 W/m^2 – 0.14 W/m^2 – 0.18 W/m^2)	0.68	W/m^2
Necessary CO_2 concentration for a radiative forcing of 0.68 W/m^2	315	ppm

Table 8: Calculation of the target level of CO2 in the atmosphere in ppm

Number of years of CO_2 sequestration for a radiative forcing of 1 W/m^2 with immediate stop of all anthropogenic greenhouse gas emissions		
Necessary reduction of CO_2 in the atmosphere in ppm to achieve 1 W/m^2: 413 - 315	98	ppm
Necessary reduction of CO_2 in the atmosphere in Gt ([11], p.9): (5.135 x 10^6 Gt x (413–315) x 10^{-6} x (44.009 x 28.966^{-1}))	765	Gt
Average additional sequestration per year on land due to CO2 fertilization, and in the ocean due to partial pressure [15]	18.6	
Average sequestration per year with a plant-based food system and reforestation according to [13]	8.1	
Average maximum sequestration per year with a plant-based food system and reforestation according to [8]	18.2	
Number of years acc. [13] (765 Gt CO_2 / (18,6 Gt CO_2 + 8,1 Gt CO_2) [15][13]	~29	Years
Number of years acc. [8] (765 Gt CO_2 / (18,6 Gt CO_2 + 18,2 Gt CO_2) [15][8]	~21	Years

Table 9: Calculation of number of years of CO_2 sequestration for 1 W/m^2 radiative forcing

Result

A global shift to plant-based food systems will allow CO_2 to be reduced from 350 ppm to 413 ppm within 13 - 18 years and radiative forcing to be reduced from 2.7 W/m^2 to 1 W/m^2 within 21 - 29 years (with a simultaneous reforestation of freed-up land and a halt to all emissions).

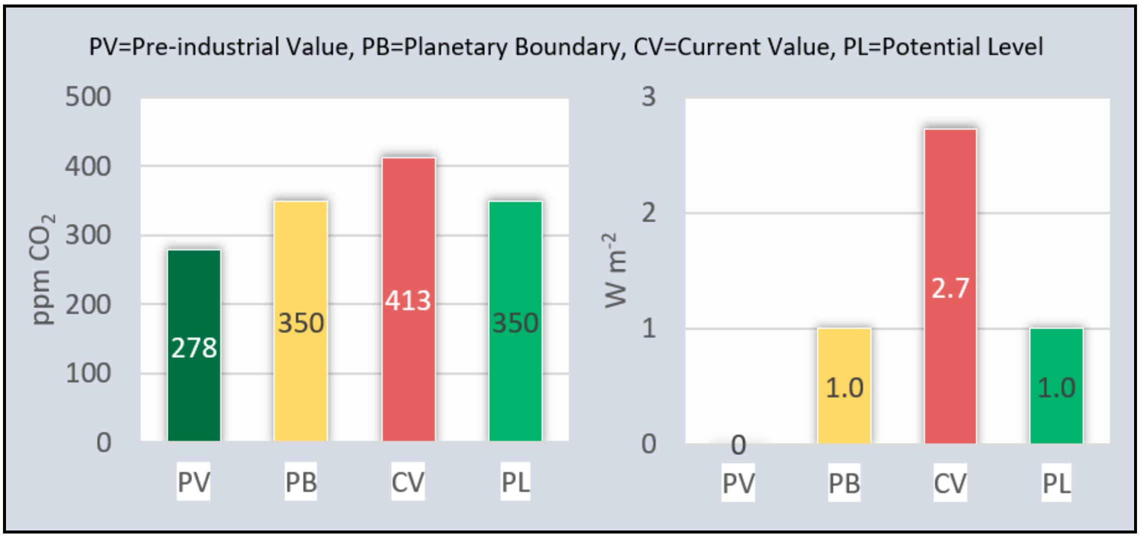

Figure 5: Achievability of Planetary Boundaries for CO_2 concentration and radiative forcing with a.) a shift to a plant-based food system, b.) reforestation, c.) halting emissions within 13 years and 21 years, respectively, at the earliest

2.4 Planetary Boundary: Biodiversity Loss

Exceeding the planetary boundary for species extinction and biodiversity loss alone can make the Earth uninhabitable for humans. The metric for the Planetary Boundary is extinctions per 1 million species per year (E/MSY).

Measured variable: Extinction of species (animals)

Background rate: 0.1 - 1 extinctions per 1 million species per year (E/MSY).

Planetary limit: 1 - 10 E/MSY

Extinction rate 2015: 100 - 1000 E/MSY (1000% - 100000%)

Calculations

Reduction of habitat use in the course of a switch to a plant-based food system		
Habitable land [5]	104	m. km^2
Use for villages, towns, roads [5]	1,5	m. km^2
Use for agriculture [5]	51	m. km^2
... use for crop production for humans (23%) [5]	11	m. km^2
... use for animal agriculture (77%) [5]	40	m. km^2
... Freed land with a plant-based food system (76%) [7].	38,8	m. km^2
Pre-industrial land use (1750 AD) [4]	11,7	m. km^2
Reduction in habitat use with a shift to a plant-based food system (38.8 million km^2 / (52.5 million km^2))	74%	

Table 10: Calculation of potential reduction in habitat uses

Result

The effects of a change to a plant-based food system on species extinction are not directly quantifiable. The causes of species extinction and biodiversity loss are multiple and usually interacting. However, the main cause is land use change. 3% of land use changes are for villages, cities and roads, 21% for crop production for humans and 76% for animal agriculture [5]. Animal agriculture is by far the largest direct cause of habitat destruction. With a shift to a plant-based food system, 74% of all anthropogenic habitat use can be reversed [7]. In addition, without animal agriculture, fresh water use, emissions of eutrophying and acidifying substances, pesticide use, and wildlife trafficking all decrease sharply.

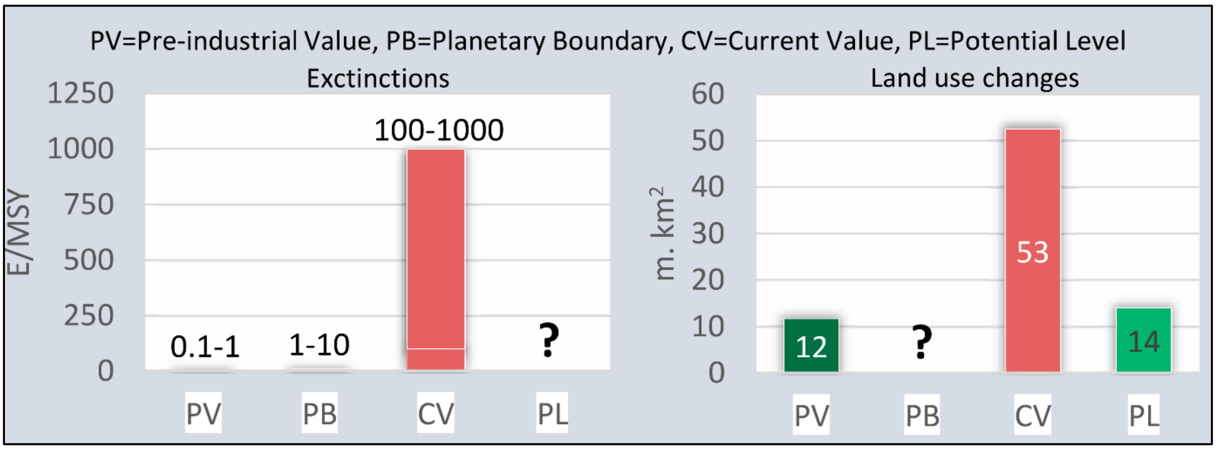

Figure 6: Exceedance of the Planetary Boundary of biodiversity loss and potential reduction of habitat use when switching to a plant-based food system.

3. Conclusion

- Of all Planetary Boundaries, the biodiversity boundary is by far the most highly exceeded.
- All other Planetary Boundaries have a reinforcing effect on the Planetary Boundary of biodiversity.
- Animal agriculture is one of the main causes for climate change, but **THE** main cause for all other three Planetary Boundaries, but especially for the one of biodiversity.
- With a phase-out of animal agriculture alone, the Planetary Boundaries for land use change could be fully achieved, and for eutrophic emissions, largely met.
- The Planetary Boundary for climate change could be achieved within 21 years with a phase-out of animal agriculture, reforestation of the released land, and a halt to emissions from all industries.
- Achieving the Planetary Boundary of biodiversity is not directly calculable. However, animal agriculture is the main cause of land use change, which in turn is the main cause of species extinction. In addition, animal agriculture has a significant impact through other factors. A phase-out of animal agriculture in combination with global reforestation is thus one of the most effective and urgent strategies against biodiversity loss.

4. References

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