Supplementary Materials for
A Welfare Economic Approach to Planetary Boundaries

1. Background information on the planetary boundaries framework

The goal of the planetary boundaries framework is to define a safe operating space for humanity on a stable and resilient Earth system, which is kept in a Holocene-like inter-glacial state (the warm, stable state of the planet we have experience since leaving the last Ice Age, some 12,000 years ago) (Rockström et al., 2009; Steffen et al., 2015). Its scientific justification arises from the empirical evidence of rapidly rising human pressures on environmental systems that regulate life support and stability of the Earth system – which are now so large that science concludes we have entered a new geological epoch, the Anthropocene (AWG, 2019; Crutzen, 2002). It is the combination of rising human pressures on the planet with growing evidence of interactions and feedbacks that risk pushing biophysical systems on Earth across thresholds, which can lead to irreversible tipping points resulting in state shifts that can undermine life conditions on Earth (Lenton et al., 2008; Lenton et al., 2019); that together constitutes the foundation of the planetary boundaries framework.

In essence, if we are approaching the ceiling of hard-wired biophysical processes and systems that regulate the state of the planet, and if we have rising evidence that this may trigger irreversible changes that can push the Earth system to drift away from the only state of the planet that we know for certain can support the world as we know it (the Holocene), then two fundamental questions arise:

1. What are the biophysical processes and systems that regulate the state of the Earth system?
2. For each of these processes/systems, is it possible to scientifically define a quantitative boundary beyond which there is a heightened risk of interactions and feedbacks that put the Holocene-like state at risk, while within which there is a high probability of safeguarding a Holocene-like state of the Earth system – a safe operating space for humanity?

These two questions form the scientific basis of the planetary boundaries framework. The planetary boundaries are therefore not a scientific attempt of ranking the most important global or regional environmental issues facing human societies. Instead, it is focused on identifying all biophysical processes and systems that contribute to regulate the state of the planet, and to set quantitative boundaries that enable planet Earth to remain in a Holocene-like inter-glacial state.

1.1 Identifying control variables and a zone of uncertainty

For each of the planetary boundary processes a control variable is identified, which is used to define the quantitative position of the boundary level (the level that defines the safe operating space). Ideally, a control variable is a key variable determining the state and functioning of a planetary boundary process (e.g., radiative forcing, W/m^2 for the climate boundary). Control variables can also be selected if they function as a proxy variable, which may be preferred if there are, e.g., long data series and ample global data access (e.g., extinction rate for biosphere integrity).

A zone of uncertainty, sometimes large, is associated with each of the boundaries. This zone represents the range of the current state of knowledge in science and intrinsic uncertainties in the functioning of the Earth system. At the 'safe', lower end of the zone of uncertainty, current scientific knowledge suggests that there is very low probability of crossing a critical threshold or significantly eroding the resilience of the Earth system. The upper end of the zone of uncertainty represents the transition into a 'danger' zone, or high-risk zone, where current knowledge suggests a much higher probability of an unwanted change to the functioning of the Earth system.

The planetary boundary (the safe level for each boundary process) is placed at the lower end of the uncertainty range. This is the only normative dimension of the planetary boundaries framework, i.e., a deliberate choice of applying the precautionary principle by placing the planetary boundary at the lower end of scientific uncertainty. Transgressing a boundary does therefore not mean that it will instantly lead to an unwanted outcome, but that the farther the boundary is transgressed, the higher the risk of unwanted regime shifts, destabilized system processes, or erosion of resilience.

1.2 Not all planetary boundary processes have planetary tipping points

Not all Earth system processes and systems included in the planetary boundaries framework have singular thresholds at the global/continental/ocean basin level. Still, they scientifically qualify as planetary boundaries if they affect the resilience of the Earth system by regulating biogeochemical flows (e.g., the terrestrial and marine biological carbon sinks), or by providing the capacity for ecosystems to recover from perturbations and shocks and continue functioning or to adapt to more slowly changing abiotic conditions. Examples of such processes are land-system change, freshwater use, change in biosphere integrity and changes in other biogeochemical flows in addition to carbon (e.g., nitrogen and phosphorus).

Such processes, while not having evidence of planetary scale tipping points, show threshold behavior at local and regional scales, which can generate feedbacks that impact on processes that do have large-scale thresholds.

1.3 A planetary boundary is not equivalent to a global threshold

As far as our current Earth system science understanding is concerned, only a few of the planetary boundary processes show evidence of planetary scale tipping points (climate change, ocean acidification, stratospheric ozone depletion), while in particular the biosphere and biochemical boundaries (biosphere integrity, freshwater use, land system change, nutrient cycles) do not show evidence of planetary scale tipping points. Instead, they have evidence of local to regional scale tipping points, and interact with global processes, determining the distance to thresholds. Furthermore, the quantitative position of the planetary boundary level – whether there are planetary tipping points or not – is not equivalent to a global threshold or tipping point. Even when a global- or continental/ocean basin-level threshold in an Earth system process is likely to exist, the proposed planetary boundary for the process is not placed at the position of the biophysical threshold but rather upstream of it, i.e., well before the threshold (at the lower end of uncertainty, applying the precautionary principle).

1.4 Nine planetary boundaries with three core boundaries

Nine planetary boundaries were identified in the first comprehensive Earth system analysis (Rockström et al., 2009), which were confirmed – with minor adjustments in the 2nd updated analysis (Steffen et al., 2015). Seven of these have quantified, while two (Novel Entities and Aerosol loading) remain unquantified (Table 1).

In the latest planetary boundaries analysis, three of the boundary processes were identified as core boundaries, suggesting a hierarchy among planetary boundaries; climate change, biosphere integrity and novel entities.

Core boundaries are defined by the evidence that they potentially could – on their own – push the Earth system away from Holocene-like conditions, and that they are high-order manifestations of interactions among several planetary boundaries. For example, the state of the climate system and the composition of species, habitats, and biomes, are biogeochemical ‘end results’ of interactions among several/all planetary boundaries.

Table 1: Planetary boundaries, control variables and quantified boundary levels with zones of uncertainty (Steffen et al., 2015).

Planetary Boundary process/system	**Control variable(s)**	**Planetary boundary level and zone of uncertainty**	**Current value of control variable**
Climate change	Atmospheric CO_2 concentration, ppm	350 ppm CO_2 (350-450 ppm)	415 ppm CO_2
	Energy imbalance at top-of-atmosphere, W m^{-2}	Energy imbalance: +1.0 W m^{-2} (+1.0-1.5 W m^{-2})	2.3 W m^{-2} (1.1-3.3 W m^{-2})
Change in biosphere integrity	Genetic diversity: Extinction rate	Genetic: < 10 E/MSY (10-100 E/MSY) but with an aspirational goal of ca. 1 M/ESY* (the background rate of extinction loss).* E/MSY = extinctions per million species-years	100-1000 E/MSY
	Functional: diversity: Biodiversity Intactness Index (BII)	Functional: Maintain BII at 90% (90-30%) or above, assessed geographically by biomes/large regional areas (e.g., southern Africa), major marine ecosystems (e.g., coral reefs) or by large functional groups	84%, applied to southern Africa only
Stratospheric ozone depletion	Stratospheric O3 concentration, DU	<5% reduction from pre-industrial level of 290 DU (5%–10%), assessed by latitude	Only transgressed over Antarctica in Austral spring (~200 DU)
Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ωarag)	≥80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80%– ≥70%)	~84% of the pre-industrial aragonite saturation state
Biogeochemical flows: (P and N cycles)	*P cycle*: Global: P flow from freshwater systems into the ocean	*P cycle*: Global: 11 Tg P yr^{-1} (11-100 Tg P yr^{-1})	~22 Tg P yr^{-1}
	Regional: P flow from fertilizers to erodible soils	Regional: 6.2 Tg yr^{-1} mined and applied to erodible (agricultural) soils (6.2-11.2 Tg yr^{-1}). Boundary is a global average but regional distribution is critical for impacts.	~14 Tg P yr^{-1}
	N cycle: Global: Industrial and intentional biological fixation of N	*N cycle*: 62 Tg N yr^{-1} (62-82 Tg N yr^{-1}). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth system, but regional distribution of fertilizer N is critical for impacts.	~150 Tg N yr^{-1}
Land-system change	Global: area of forested land as % of original forest cover	Global: 75% (75-54%) Values are a weighted average of the three individual biome boundaries and their uncertainty zones	62%
	Biome: area of forested land as % of potential forest	Biome: Tropical: 85% (85-60%) Temperate: 50% (50-30%) Boreal: 85% (85-60%)	
Freshwater use	Global: Maximum amount of consumptive blue water use (km^3yr^{-1})	Global: 4000 km^3 yr^{-1} (4000-6000 km^3 yr^{-1})	~2600 km^3 yr^{-1}
	Basin: Blue water withdrawal as % of mean monthly river flow	Basin: Maximum monthly withdrawal as a percentage of mean monthly river flow. For low-flow months: 25% (25-55%); for intermediate-flow months: 30% (30-60%); for high-flow months: 55% (55-85%)	
Atmospheric aerosol loading	Global: Aerosol Optical Depth (AOD), but much regional variation		
	Regional: AOD as a seasonal average over a region. South Asian Monsoon used as a case study	Regional: (South Asian Monsoon as a case study): anthropogenic total (absorbing and scattering) AOD over Indian subcontinent of 0.25 (0.25-0.50); absorbing (warming) AOD less than 10% of total AOD	0.30 AOD, over South Asian region

Introduction of novel entities	No control variable currently defined	No boundary currently identified, but see boundary for stratospheric ozone for an example of a boundary related to a novel entity (CFCs)

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