

# The Planetary Accounting Framework:

A novel, quota based approach to understanding the planetary impacts of any scale of human activity in the context of the safe-operating-space

~ Kate Meyer & Peter Newman ~

## Appendix: How the Planetary Quotas are Determined

### The Carbon Quota

#### *The indicator:*

Carbon dioxide (CO<sub>2</sub>) is a greenhouse gas (GHG) emitted during the combustion of fossil fuels and the production of cement. CO<sub>2</sub> can actively be removed from the environment through vegetation and forestation[1], or through geoengineering[2]. The anthropogenic emissions of CO<sub>2</sub> are the single biggest human contribution to climate change[3].

The term carbon footprint, which dates back to 1979 [4], is extensively used in a wide range of applications from basic online calculators to detailed life-cycle analyses of products, regions or nations [4, 5]. It forms the underpinning of carbon accounting. There is no single definition or methodology for the term. However, it always includes a measure of gross emissions of CO<sub>2</sub>, usually reported in units of mass. It is common for carbon footprint assessments to include the emissions of other GHGs in which case the unit used is a measure of global warming impacts – communicated as the mass of CO<sub>2</sub> emissions that would result in *equivalent* global warming (CO<sub>2</sub>e).

Warming impacts of GHGs are often reported in terms of equivalent CO<sub>2</sub> emissions. However, it is not the case that a reduction in other GHGs can offset the environmental impacts of CO<sub>2</sub>. This is because the lifetime of CO<sub>2</sub> is so much longer than the lifetime of other greenhouse gases, even those termed “long lived”. The Planetary Boundary indicators for climate change articulate this important differentiation through the inclusion of two distinct limits: the atmospheric concentration of CO<sub>2</sub>, and total radiative forcing. As such, the Quota for CO<sub>2</sub> emissions is distinct from other greenhouse gases for the Quotas to represent the same operating space as the Boundaries.

Carbon footprints are generally reported in terms of gross emissions rather than net emissions. The current atmospheric concentration of CO<sub>2</sub> ≈ 400ppm (parts of CO<sub>2</sub> per million parts of atmosphere) [6] is greater than the Planetary Boundary limit of 350ppm. It follows that the Quota for CO<sub>2</sub> must be negative.

The indicator for CO<sub>2</sub> is thus the “net carbon footprint”, defined as total CO<sub>2</sub> emissions less total CO<sub>2</sub> uptake, measured in kilogramss (or tonnes) of CO<sub>2</sub>.

#### *The limit:*

There are four upstream PBs that have been considered in the determination of the carbon Quota:

- climate change: atmospheric concentration of CO<sub>2</sub> ≤ 350ppm;
- ocean acidification: aragonite saturation state of the oceans ≥80% of the pre-industrial level;

- biosphere integrity: global extinction rate  $\leq 10$  E/MSY;
- climate change: total radiative forcing  $\leq \pm 1\text{W/m}^2$ .

The oceans absorb  $\text{CO}_2$  from the atmosphere at a rate approximately proportional to the concentration of  $\text{CO}_2$  in the atmosphere. Returning to an atmospheric  $\text{CO}_2$  concentration  $\leq 350\text{ppm}$  will mean that the Boundary for ocean acidification is intrinsically respected [7].

Climate change is one of five primary pressures leading to species extinctions[8]. An atmospheric concentration of  $\text{CO}_2 \leq 350\text{ppm}$  is considered safe for humanity. This does not mean that there would be no climate change or warming, but that it would be limited to  $\approx 1.7^\circ\text{C}$ [9]. There is no specific concentration of  $\text{CO}_2$  considered “safe” with respect to extinction rate. In the absence of specific level for biosphere integrity, we have assumed that a concentration of  $\text{CO}_2$  in the atmosphere  $\leq 350\text{ppm}$  will be an adequate limit to respect the pressure for extinction rate.

Total radiative forcing is the most holistic measure of global warming/cooling and comprises all GHGs as well as albedo (reflectivity of Earth’s surface which changes with land-use change) and the emission of aerosols (particles suspended in the atmosphere). There are four Quotas, which contribute to total radiative forcing and must collectively respect the Boundary of  $\leq \pm 1\text{W/m}^2$ ; the carbon, menox, land, and aerosol Quotas. The impact of the carbon Quota on the collective forcing of the four Quotas is discussed under the aerosol Quota section.

The rate of  $\text{CO}_2$  uptake required to return atmospheric  $\text{CO}_2$  concentration to 350ppm depends on the timeframe selected. There is only one pathway proposed in the academic literature which is estimated to return  $\text{CO}_2$  levels to 350ppm within this century. In 2013, former NASA Chief Climate Scientist James Hansen et al proposed a pathway of rapid reductions in emissions and substantial carbon uptake from reforestation and biochar capture [9]. They estimated that this pathway would yield an atmospheric concentration of 350ppm in 2100. Their pathway included 6% emission reductions from 2015 onwards. We did not take this pathway. Their paper includes a proposal for the more rapid emissions reductions that would be required if emission reductions did not start until 2020. Under this scenario, emission reductions of 15% per year are required from 2020.

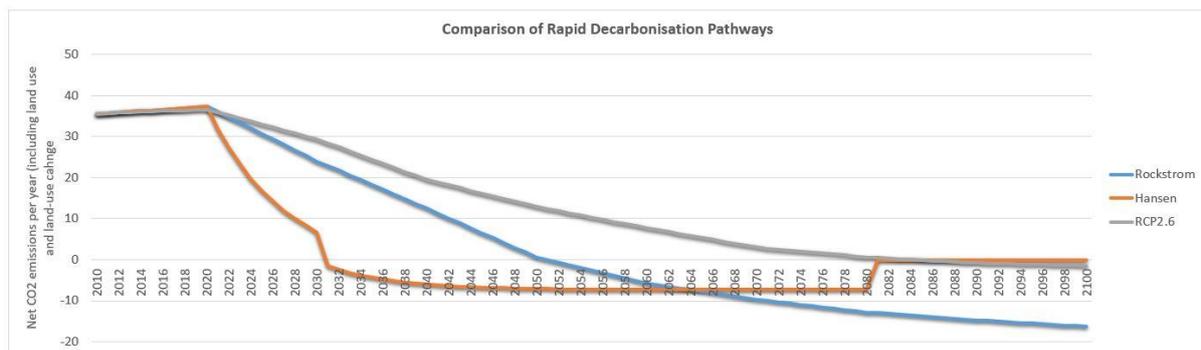
There are two other rapid decarbonisation pathways which should be considered, although neither return concentration levels to within the Boundary level within this century. The first is representative concentration pathway (RCP) 2.6. This is one of four RCPs – future scenarios considered in The Fifth Assessment Report by the International Panel for Climate Change (IPCC). RCP2.6 is the most stringent of the four scenarios. The second, is a decarbonisation pathway proposed by Planetary Boundaries author, Rockstöm et al in 2017 [10].

RCP2.6 begins with gradual emissions reductions of approximately 2% per annum starting in 2020. These reductions increase gradually to approximately 4% by mid-century and 15% by 2080. From 2100 on RCP2.6 shows constant gross negative emissions of approximately  $-3.7\text{GtCO}_2/\text{yr}$  ( $-1\text{GtC}/\text{yr}$ ), with net emissions (including land use and land-use change) of approximately  $-1.5\text{GtCO}_2/\text{yr}$ . The negative emissions in this scenario are expected to be achieved through high energy efficiency, renewable power, and biomass energy with carbon capture and storage (BECCS) [11]. The estimated concentration of  $\text{CO}_2$  in the atmosphere in 2100 under this scenario is 420ppm [12].

Rockstöm et al’s pathway is quite different to the others. This scenario has less severe emissions reductions than Hansen et al’s pathway at the start (beginning in 2020), of approximately 4% per year until 2030. From 2030 – 2050 he shows much greater reductions that vary in range from 5% - 11% per year and include a much bigger proportion of carbon extraction later to make up for the slower start. The reductions return to 3-4% from 2050 – 2100. The authors estimate that this

pathway would result in a CO<sub>2</sub> concentration of approximately 380ppm by 2100 – still outside the Planetary Boundary of 350ppm. This agenda is currently being addressed by the IPCC, and other scenarios are likely to be addressed as a result.

The net emissions (including emissions from land use and land-use change) of these three pathways are shown in Figure 1. In keeping with the precautionary principle, we have set the Quota based on Hansen et al's [9] pathway. Rockström et al's [10] pathway is more gradual, relies on uncertain technology, and does not meet the Planetary Boundary this century. RCP2.6 is even more gradual, and does not meet the Planetary Boundary until after 2300.



**Figure 1: Net annual CO<sub>2</sub> emissions proposed for decarbonisation pathways to return to CO<sub>2</sub> concentrations of 350 (Hansen et al), 380ppm (Rockstrom et al) and 420ppm (RCP2.6) by the end of the century**

Planetary Quotas define end goal targets and not the pathways (or in most cases the timeframes) to reach these. Determining a single Quota for net CO<sub>2</sub> emissions does however require a level of judgement regarding timeframe. When Hansen et al [9] first proposed the pathway in 2013, only 6% reductions were required each year from 2015. Delaying this by only 5 years means that reductions of 15% per year are now required to achieve the same result. The timing for emission reductions is extremely critical. We propose an initial Carbon Quota of -7.3GtCO<sub>2</sub>/year. We qualify this Quota as follows:

1. Rapid CO<sub>2</sub> emission reductions must begin by 2020 at the latest.
2. Net CO<sub>2</sub> emissions must reach 0 by 2030.
3. The Quota must be met by 2050.

This Quota in particular should be monitored and revised frequently as human activity over the next few years could alter this substantially.

## The Menox Quota

*The indicator:*

The Planetary Boundary for radiative forcing indirectly includes limits for all greenhouse gases, i.e CO<sub>2</sub>, methane (CH<sub>4</sub>), nitrous oxide (NO<sub>x</sub>), halocarbons, hydrofluorocarbons (HFCs), perfluorinated chemicals (PFCs) and sulphur hexafluoride (SF<sub>6</sub>) as well as limits for aerosols and aerosol precursors and change in land albedo.

Emissions of CO<sub>2</sub> and halocarbons, aerosols and precursors, and effects of albedo change are not equivalent metrics with respect to the Planetary Boundaries. Limits for these pressures are included in the Carbon, Air Quality, and Land Quotas. The emission of HFCs, PFCs and SF<sub>6</sub> are excluded from the critical pressures included in the Planetary Quotas as they contribute less than 1% each, and together less than 5%, to the corresponding Boundary – radiative forcing [13].

The remaining greenhouse gases are CH<sub>4</sub> and NO<sub>x</sub>. As previously in the previous section, the warming impacts of GHGs are often equated to an equivalent mass of CO<sub>2</sub> emissions via warming potential. This indicator corresponds well to the relevant Boundary indicator - radiative forcing which is a measure of warming/cooling. However, the name of this indicator is generally either carbon footprint or greenhouse gas footprint. Both of these would be inaccurate in this instance. We thus propose a modified greenhouse gas footprint – the “menox footprint”. The menox footprint is measured in net warming impacts of CH<sub>4</sub> and NO<sub>2</sub> emissions measured in kgs (or tonnes) of CO<sub>2</sub>e.

*The limit:*

There is no specific limit for methane or nitrous oxide within the Planetary Boundaries. The combined effects of methane, nitrous oxide, carbon dioxide, aerosols and land albedo are limited by the Planetary Boundary for radiative forcing of  $\leq \pm 1\text{W/m}^2$ .

The IPCC scenario RCP2.6 shows end of century emissions for methane of  $\leq 150\text{Mt/year}$  and nitrous oxide of  $\text{N}_2\text{O} \leq 5\text{Mt/year}$  [12]. These targets are less ambitious than the target for carbon dioxide under this scenario because there is less potential for abatement of these gases from agriculture [11]. The values are based on a reduction to almost zero energy related emissions of methane and zero process related emissions of nitrous oxide [11]. A breakdown of these values shows that almost all of the methane and nitrous oxide emissions in this scenario are predicted to come from agriculture. Van Vuuren et al [11] have identified that there will be conflicting needs for land use – reforestation and bioenergy carbon capture and storage (BECCS), food production, and biodiversity. These values for methane and nitrous oxide are thus set in order to maximise food production per unit area.

RCP2.6 is named as such based on the predicted forcing in 2100 of  $2.6\text{W/m}^2$ . It comes close to, but does not meet the Boundary for radiative forcing by 2500 [14]. However, in the pathway proposed by Hansen et al [9], there is no requirement for reductions in non-CO<sub>2</sub> greenhouse gases. His pathway is based on a constant net forcing from non-CO<sub>2</sub> GHGs and aerosols (therefore that they are approximately equal and opposite as they are today).

The interrelationship of the different Quotas is discussed in the Aerosol Quota section to show that collectively, the Quotas do respect the PB for radiative forcing.

Converting these limits to the control variable unit CO<sub>2</sub>e and combing them gives the Menox Quota of  $\leq 5.24\text{GtCO}_2\text{e/yr}$

## The Land Quota

*The indicator:*

The original PB indicator for land-use change was the percentage of global ice-free land surface converted to cropland [15]. This was updated in 2015 to be forest area  $\geq 75\%$  of original forest area [7]. The updated limit was based on the regulation of the climate system and hydrological cycle. The current status of global forested land is 62% of original – i.e. we have exceeded this Boundary [7].

Land-use is a PB, but is also a pressure with respect to other PBs:

- *climate change* – radiative forcing  $\leq \pm 1\text{W/m}^2$  and atmospheric concentration of CO<sub>2</sub>  $\leq 350\text{ppm}$ ;
- *atmospheric density* - atmospheric aerosol density  $\leq 0.1$ ;
- *biosphere integrity* – extinction rate  $\leq 10 \text{ E/MSY}$ .

Land use effects climate change in two key ways. Clearing forests or increasing urban areas changes the reflectivity of Earth’s surface and therefore the total radiative forcing (heat balance at Earth’s surface). Forests are also a primary carbon sink.

Clearing forest for use in agriculture can change the hydrology of the land and therefore result in desertification. This in turn allows more sand and dust to be released into the atmosphere – contributing aerosols to the atmosphere.

Land use pressures on extinction rate are two-fold – destruction of habitat from land-use change, and associated CO<sub>2</sub> emissions contributing to climate change. There is a specific Biodiversity Quota, however for completeness, biodiversity is also considered here.

There are many existing land use indicators, the most renowned of which is the Ecological Footprint. Ecological Footprint is a measure of natural capital required for a system (person, group, product) expressed in a proprietary unit of area, “global hectares” which incorporates weighting factors for different land types to express land area functionality [16]. The weighting system used for the Ecological Footprint (and weightings when used for other environmental indicators) are criticised for over simplifying and under communicating the environmental problems [17]. These weighting systems make this indicator unsuitable for the Land Quota. It would not be possible to correlate an Ecological Footprint accurately with a Boundary for a specific area type – i.e. forest.

To best meet the intent of the land-use Boundary - percentage of original forest area – the Quota should consider forest area directly. A forest area indicator would also suit the other Boundaries well:

- Climate change: Hansen’s pathway to 350ppm described in the supplementary information for the Carbon Quota includes a specific target of 100GtC of uptake via forestry and biochar storage [9].
- Atmospheric density: clearing forest is the primary driver for desertification leading to increased dust particles in the atmosphere
- Biosphere integrity: forest is also the most important land type for biodiversity [8].

The term forest footprint has been used by the World Wildlife Fund to refer to the area needed to produce the forest products consumed by a certain activity or group [18]. We propose an alternative metric – deforestation footprint defined as the net change of land area to and from forestland measured in square kilometres. We chose the unit deforestation rather than forest area or reforestation intentionally. It is conventional for footprints to increase as impacts increase. The use of deforestation footprint allows this indicator to follow this convention. A negative value implies reforestation.

*The limit:*

The world’s surface is 15 billion ha. Only 6.5 billion ha of this is suitable for forestry. Table 1 shows global Quota estimates for the deforestation footprint based on each of the corresponding Boundaries.

**Table 1: Summary of Land Quota limits based on different upstream Boundaries**

Planetary Boundary	Corresponding Limit	Basis
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Land-use change >75% original forest area restored	≤ -0.9 Gha gross ≤ -11 Mha/yr	75% of original forest area equates to total forest area of 4.9billion hectares. Current forest area is approximatley 4 billion hectares.
Climate change: CO <sub>2</sub> concentration ≤ 350ppm	≤ -0.9 Gha gross ≤ -11 Mha/yr	This would require reforestation between 0.6[19] – 0.9[20] billion ha by 2100. At the high end of this range this equates to total forest area of 4.9 billion ha.
Biosphere integrity: Extinction rate ≤ 10 E/MSY	NA	There is no specific global land-use value that relates to extinction rate. There are estimations of how much land should be retained for biosphere integrity - the “biodiversity buffer” which range from 1% [21], 10-25% [22, 23], 75% [24], to 99%[21]. Land use impacts on biosphere integrity are included explicitly in the biodiversity Quota. As such, we consider the estimates for land-use and climate change to be sufficient in determining the Quota for land use.
Atmospheric density: atmospheric aerosol density ≤ 0.1	NA	The Boundary for atmospheric density does not define the make up of the aerosols – simply an upper limit. However, a negative deforestation limit for the Land Quota implies an increase in forest area and thus a likely reduction in dust aerosols over time.

We therefore propose a land Quota of forest footprint ≤ -11 Mha/yr.

### The Ozone Quota

*The indicator:*

Human emissions of ozone depleting substances (ODPs) such as CFCs, halons, and HCFCs created a hole in the ozone layer – the layer of the atmosphere which protects life on Earth by filtering most of the ultraviolet radiation from the sun before it reaches Earth’s surface. The story of the hole in the ozone layer is one that conveys not only the significance of human activity on the functioning of the Earth system, but also the opportunity for successful human management of the Earth system to bring us back from dangerous environmental tipping points. In 1987, in response to the hole in the ozone layer, world leaders agreed on the Montreal Protocol, a global accord to phase out key ODPs – now known as “Montreal gases” [7]. This phase out, which will not be complete until 2030, has already led to a substantial decrease in the size of the hole. Scientists estimate that the layer will be “repaired” by 2050 [25].

There is no existing indicator to assess the emission of Montreal gasses, I therefore propose a new indicator – ozone footprint, a measure of the gross emissions of Montreal gases in kgs (or tonnes).

*The limit:*

The Montreal Protocol comprises a complete phase out of Montreal gasses by 2030 indicating that there is no acceptable level of emissions of Montreal gasses. We thus propose a preliminary ozone Quota of ozone footprint = 0kg.

### The Air Quality Quota

*The indicator:*

Aerosols are small particles suspended in the air. Aerosols can be emitted directly (sea salt in the atmosphere is one of the most common naturally occurring aerosols), or can develop from the emission of precursor gases. The main anthropogenic sources of aerosols include dust (due to desertification), and emissions of sulfur oxides, nitrogen oxides, dimethyl sulfide, organic carbon, black carbon, and volatile organic compounds[26]. Atmospheric aerosol loading was included as a Planetary Boundary due to the influence of aerosols on the climate system through changes to radiative forcing (predominantly cooling), and impacts on human health [27]. Air pollution has been identified by the World Health Organisation (WHO) as the single greatest risk for global health[28].

The PB indicator for aerosol density is aerosol optical depth (AOD), a unitless dimension which indicates the fraction of sunlight which cannot reach the ground due to interactions (absorption and scattering of light) with aerosol particles. A value of 0 indicates perfectly clear skies, 1 indicates that no light is transmitted. The global mean value at 550nm is approximately 0.12 – 0.16 [29].

There is no indicator in the academic literature that links human activity to aerosols (or air quality). However, Meyer and Ryberg have recently developed a new indicator to do this – the air quality footprint, measured in a novel unit – *equivalent aerosol optical depth (AODe)* (described below). AODe is not an estimation of the resultant AOD due to an activity. Estimating the resultant AOD would be enormously challenging and likely inaccurate due to the highly complex behaviour of aerosols. AODe is the *estimated change in average AOD due to the emissions of aerosols or precursor gases*. The purpose of this indicator is not accurately estimate the air quality due to a particular activity. This is a novel adaptation of the AOD metric is designed to facilitate the estimation and communication of the relative air quality impacts of different activities and allow these to be compared to a global limit (the Aerosol Quota). The concept is in keeping with the convention for equating impacts of non-CO<sub>2</sub> gases with CO<sub>2</sub> using global warming potential to derive the “equivalent CO<sub>2</sub> impacts (CO<sub>2</sub>e). The calculation method builds on work by Ryberg linking life cycle assessment indicators with the PBs (publication imminent). AODe is based on the estimation of aerosol mass loading per unit area following the emission of an aerosol or precursor as a function of specific extinction of the aerosol and the atmospheric residence time.

#### *The limit:*

There are several upstream Boundaries that must be considered in the development of a global aerosol Quota:

- *atmospheric aerosol density* – AOD;
- *climate change* - radiative forcing;
- *biosphere integrity* – extinction rate (air quality);

There is no global PB limit defined for aerosols, however in the most recent update of the boundaries, a regional limit of aerosol optical depth (AOD)  $\leq 0.25$  was proposed. To account for the fact that many aerosols occur naturally, a specific limit for anthropogenic aerosols was also defined:  $AOD_{anthro} \leq 0.1$  [7]. This limit was set on the basis of limiting impacts on the ocean-atmospheric circulation [7].

There is no specific air quality guideline pertaining to extinction rate. The concentration of aerosols in the atmosphere is often used as a proxy for air quality – measured in terms of micrograms of particles per volume of air ( $\mu\text{g}/\text{m}^3$ ) – typically differentiated by particle size (diameters  $\leq 2.5\mu\text{m}$  (PM<sub>2.5</sub>) or  $\leq 10\mu\text{m}$  (PM<sub>10</sub>). The WHO have proposed minimum air quality standards for human health[30]:

- PM<sub>2.5</sub>: 10 µg/m<sup>3</sup>
- PM<sub>10</sub>: 20 µg/m<sup>3</sup>

These limits are assumed to be acceptable for other species.

There have been numerous studies linking AOD to both radiative forcing e.g. [31, 32] and PM<sub>2.5</sub> e.g. [33-38]. Both these methods have been used in the development of the aerosol Quota

### Radiative Forcing

Radiative forcing due to stratospheric aerosols depends predominantly on the aerosol optical depth. The adjusted forcing due to aerosols can be approximated as follows [31, 32, 39]:

$$-25 \times \text{AOD} \approx \text{RF}_{\text{Aero}}$$

The Boundary for radiative forcing is  $\pm 1 \text{ W/m}^2$ . As discussed previously, the forcings resulting from the carbon, menox, ozone, land, and aerosol Quotas must collectively respect this Boundary in order for the Quotas to respect the safe-operating-space.

$$\text{RF}_{\text{total}} \approx \text{RF}_{\text{CO}_2} + \text{RF}_{\text{NCGs}} + \text{RF}_{\text{LU}} + \text{RF}_{\text{Aero}}$$

The carbon Quota equates to a CO<sub>2</sub> forcing:  $\text{RF}_{\text{CO}_2} \approx 1.23 \text{ W/m}^2$ .

Together, the menox and ozone Quotas (and using RCP2.6 levels in 2100 for other non-CO<sub>2</sub> GHGs), equate to a non-CO<sub>2</sub> GHG forcing:  $\text{RF}_{\text{Non-CO}_2\text{-GHGs}} \approx 0.7$  (derived from [11]).

It is not straightforward to predict the level of impact that the land Quota would have on radiative forcing. However, increasing forest area would decrease surface albedo and reduce the amount of negative forcing. The change in land use since 1870 lead to a change in albedo with a radiative forcing impact estimated at  $-0.15 \pm 0.1 \text{ W/m}^2$  [40]. The estimated radiative forcing based on the proposed land Quota is thus  $-0.15$  to  $0 \text{ W/m}^2$ .

To respect the total radiative forcing limit of  $\pm 1 \text{ W/m}^2$ , it follows that the aerosol Quota forcing ( $\text{RF}_{\text{Aero}}$ ) must fall between  $-0.93$  and  $-2.78 \text{ W/m}^2$ . Thus the aerosol Quota must be  $0.04 \leq \text{AODe} \leq 0.11$ .

### PM<sub>2.5</sub>

The estimated relationship between AOD and PM<sub>2.5</sub> is less consistent in the literature eg[33] [37] [38] [36] [34]. Using the recommended PM<sub>2.5</sub> concentration (as the more stringent of the WHO recommendations) in each of the formulae listed in the cited studies yields AODs ranging from 0.114 ([37, 38]) to 0.209 [36].

Despite the range of almost 100% from lowest to highest, these calculations indicate that a limit based directly on the PB limit – i.e.  $\text{AODe} \leq 0.1$  – would respect the WHO air quality recommendations. This is consistent with the academic literature which typically refers to AOD values of this order of magnitude as low, or pertaining to clear skies e.g. [33, 37, 41].

Considered in isolation, the lower the air quality footprint the better. The WHO state that there is no level of air pollution that has no health impacts and that the lowest PMCs possible should always be targeted [42]. However, as aerosols provide a predominantly cooling forcing, they also offset some of the warming impacts of GHG emissions and land-use change. Without aerosols, average global temperatures would be higher. It would be theoretically possible to reduce the limits for the carbon, menox and land Quotas so that it would be possible to concurrently experience perfectly clean air

and respect the safe-operating-space. These Quotas are already very challenging however, and an air quality footprint  $\leq 0.1$  (AODe) represents clear skies.

We therefore propose an Air Quality Quota of  $0.04 \leq \text{air quality footprint} \leq 0.1$ .

## The Nitrogen and Phosphorous Quotas

### *The indicators:*

The PB indicators for nitrogen and phosphorous are already pressure indicators but not indicators which are already used for environmental assessments. I have proposed slight modifications to these indicators accordingly, as shown in Table 2:

**Table 2: Modification of nitrogen and phosphorous Boundary indicators**

Planetary Boundary	Planetary Quota
Phosphorous flow from freshwater systems into the oceans	Phosphorous footprint – defined as the amount of phosphorous released to the environment
Industrial and intentional biological fixation of nitrogen	Nitrogen footprint – defined as the total amount of reactive nitrogen released to the environment

### *The limits:*

All phosphorous released to the environment ends in the oceans, and therefore the Boundary and Quota should be the same value: phosphorous footprint  $\leq 11\text{Tg/yr}$ .

Nitrogen consumed by humans can be removed from waste water before it is released to the environment through a process called denitrification. The PB indicator for nitrogen accounts for all fixated nitrogen – i.e. denitrification is not considered. Nitrogen footprint accounts only for fixated nitrogen that is then released to the environment – i.e. denitrification is considered.

The basis for the PB nitrogen limit is the eutrophication of aquatic systems and therefore denitrification reduces these impacts. I thus propose a preliminary nitrogen Quota of nitrogen footprint  $\leq 62 \text{ Tg/yr}$  – the same limit as the nitrogen Boundary.

## The Water Quota

### *The indicator:*

In environmental impact assessments, water is often categorised as either *green* (rainwater), *blue* (surface and groundwater), or *grey* (the amount of freshwater required to dilute contaminated water to acceptable standards)[43].

The regional availability of water has led to much controversy over the existence of a global limit for water. There have been debates between water experts in the water footprint and life cycle assessment fields as to how regionality should be dealt with[44-48]. These debates have led to two key pressure indicators which can be used to assess water consumption due to human activity – the water footprint [49] and the weighted water footprint [45]. Both account for direct water consumption and virtual water consumption - water used in the development of goods and services. The key difference between these indicators is that the water footprint counts net water consumed with no mechanism to account for the scarcity of the water source [49]. The weighted water footprint attempts to add a water scarcity factor to account by weighting different sources within the calculations [46].

Regional water scarcity is very important to the overall functioning of the Earth System. However, I do not agree with the weighted water footprint method as a mechanism to account for this. To explain the impacts of the two approaches on resulting water footprints, we use the example of two cans of baked beans. Let us assume that can #1 has an (unweighted) water footprint of  $20\text{m}^3$ , can #2 of  $5\text{m}^3$ . These results communicate that it took 4 times more water to produce can#1 than can#2. The production of can#1 can thus be considered relatively inefficient with respect to water consumption.

Now let us assume that can#2 is produced using water from a water body that is 2 times as water scarce as the first. Using the weighting water footprint method this would give water footprints of  $10\text{m}^3$  for each can of beans. This communicates that the two cans are environmentally equivalent. The validity of this message is arguable. The calculations consider efficiency and scarcity, but the results do not communicate either in a transparent way. We agree with the position of the weighted water footprint authors - that both the net water consumed and the source of the water used should be communicated. However, without a better mechanism to communicate water scarcity – which does not cache the total water used – we propose to use the original water footprint as the indicator for the PQs. An alternate means for communicating water scarcity via a product labelling application of Planetary Accounting is discussed later in the paper.

The determination of a water indicator goes beyond the debate of scarcity weightings. One must also consider which components of the water footprint to include (i.e. green, blue, grey).

The water Boundary is a limit for *gross blue water consumption*. The authors of the PB framework acknowledge that green water is a scarce resource and should be considered within the PBs. However, because of the inherent difficulty in defining a freshwater boundary that encompasses greenwater, they set a consumptive blue water use limit as a preliminary measure [7, 15].

The exclusion of green water from the Quotas would be problematic in some of the potential applications – for example comparing impacts of products. 74% of the global average water footprint of production between 1996 – 2005 was from green water[50]. Using blue water from a water rich source to irrigate crops may have less impact on global water scarcity than using rainfed land for crops that would otherwise have been habitat for natural ecosystems. Thus only reporting blue water would give an incomplete picture.

The inclusion of grey water in the Quota indicator presents an opportunity to include a proxy for the PB - novel entities (chemical pollution). There is no metric or limit proposed for the novel entities Boundary at this stage. It is common practise to use water pollution as a proxy measure for chemical pollution[51], so while a specific Boundary does not exist, the need for a Boundary can be somewhat addressed through the inclusion of grey water in the water Quota indicator.

We therefore propose to use net water footprint as the water Quota indicator – defined as the net volume green, blue, and grey water consumed.

#### *The limit:*

There is no scientific consensus on a global limit for total net water consumption. However, on the basis that more than 30% of major groundwater sources are being depleted, some experts argue that a precautionary approach would be to set the limit no higher than current net global water consumption[52].

We therefore propose a preliminary water Quota of net water footprint  $\leq 8500\text{km}^3$ .

## The Biodiversity Quota

*The indicator:*

The human causes of biodiversity loss are complex and not completely understood [53, 54]. However most of the literature agrees that the five primary anthropogenic threats (Pressures) contributing biodiversity loss are [15, 53, 55-57]:

- Climate Change
- Landuse change (habitat loss)
- Pollution (eutrophication, air, other (chemical))
- Overexploitation of species
- Introduction invasive of species

Climate change is a pressure with respect to biodiversity loss. When considered within the DPSIR framework it is an Impact. Climate change is also one of the Planetary Boundaries (with two distinct global limits). The Pressures with respect to the Boundaries for climate change are dealt with via the carbon, methane, ozone, aerosol, and land Quotas. We therefore consider this Pressure on biodiversity loss to be sufficiently addressed by the Quota framework.

Landuse change is also a Planetary Boundary and there is a specific land Quota. The impacts of the land Quota limit on biodiversity loss are considered, however the correlation between the Boundary for Biosphere Integrity and the land Quota is loose.

Pollution is a very broad term. The literature on pollution as a Pressure for biodiversity loss breaks this down into components: eutrophication, air, other (chemical). Eutrophication limits are addressed within the nitrogen and phosphorous Quotas. Air pollution within the air quality Quota. Chemical pollution is addressed in proxy via the greywater component of the water Quota. None of Quotas address plastic pollution which is fast becoming one of the major threats to marine life [58].

The overexploitation of species is predominantly from uncontrolled and/or illegal hunting and fishing [8]

The introduction of invasive species has many different pathways. A study by the Convention on Biodiversity CBD [59] summarised the primary drivers for over 500 invasive species and found over 40 drivers ranging from purposeful release for measures such as erosion control, and hunting, to escape of pets, contamination of international trade objects, and stowaways on container ships. These were categorised into 5 major groups – release, escape, transport-contamination, transport-stowaway, corridor, and unaided.

It is not straight forward to assign scaleable responsibility to such varied mechanisms as are present in the overexploitation and introduction of invasive species.

It is common practice to deal with the complexity of biodiversity drivers by the use of a proxy, land use based indicator.

The magnitude and diversity of Pressures with respect to biodiversity loss makes it very difficult to determine one or even 2-3 indicators which can address all of these Pressures. For this reason, the use of land based indicators as a proxy for biodiversity is common practise. Sustainable Development Goal (SDG) 15 - Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss – the most explicit SDG with respect to biodiversity loss, includes several land based indicators in their proposal of suitable indicators to measure this goal including[60]:

- Forest area as a percentage of total land area
- Forest cover under sustainable forest management
- Percentage of land that is degraded over total land area

In a UNEP report on life cycle indicators, the need for a scaleable indicator to assess the land use related impacts on biodiversity was identified and a new indicator proposed[61]. The indicator proposed is called the *percentage disappeared fraction* (PDF) of species. This indicator is very similar to the Planetary Boundary for biosphere integrity – *extinction rate* as both are expressed in terms of the percentage of extinct (or disappeared) species. The difference between the two is in the calculation. Extinction rate is determined through observation – it is an Impact indicator. In contrast PDF is an estimation based on land use data – thus a Pressure indicator.

In the absence of an indicator that can suitably address the varied Pressures with respect to biodiversity loss, we have selected the percentage disappeared fraction as the indicator for biodiversity.

The purpose of the UNEP report was to propose indicators that allow better consistency in the development and communication of green products. This differs to the purpose of the Quotas in that the Quotas are intended to be the basis of a global Planetary Accounting system that can be used for any scale of human activity. In the instance of the UNEP report, there is little need to account for positive land transformation – as such, all of the “correction factors” – numbers used to convert land transformation to percentage disappeared fraction – are positive (i.e. they lead to biodiversity loss). For the purpose of the Planetary Accounting framework, further work will be required to determine correction factors for positive transformation which results in biodiversity gains.

We therefore propose to the indicator for the biodiversity Quota *net biodiversity footprint* measured in *net PDF*.

*The limit:*

The indicator proposed differs from the Boundary only in the measurement/calculation method. As such we propose to use the Planetary Boundary figure of 10 species per million species per year, therefore Biodiversity Footprint  $\leq 1E-4$  PDF.

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