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 ~

Abstract

The Planetary Boundaries represent a breakthrough in the understanding of Earth System science. The Boundaries define the "safe-operating-space" beyond which the risk of an abrupt and potentially irreversible change in the state of the planet is high.

Policy makers and scientists have attempted to downscale the Boundaries for use at different levels, however, they were not designed to be scaled. The Boundaries are not easily translated into personal or policy action that is measurable and scaleable. This paper shows how that can be done.

The paper introduces a new approach – The Planetary Accounting Framework - to communicate scientific limits in the context of any scale of human activity. This framework has been developed by combining innovations from Earth System Science, Management Theory and Environmental Accounting. It is based on nine "Planetary Quotas", global limits which represent the same safe-operating-space as the Boundaries. The paper shows how each Quota has been derived from an understanding of the science of Earth System processes using the Driver-Pressure-State-Impact-Response framework from environmental accounting so they are applicable to the management theory of poly-scalar systems.

The Planetary Accounting Framework shows for the first time how individual actions, city level infrastructure, and national policies can be expressed in terms of the Planetary Boundaries. Meaningful decisions can now be made at various scales on regulating activities, urban planning, design and technology by local policy makers, institutions, industry and all levels of government. The framework could be used to incorporate the true value of key environmental currencies into existing global economic structures. It enables the practical application and communication of the Planetary Boundaries to all scales of human activity.

Introduction

There have been major advances in recent years in our understanding of scientific planetary limits through Earth System science - now known as the Planetary Boundaries (PBs)[1, 2] - in our understanding of the social science of change – or management theory [3, 4] – and in our capacity to estimate the environmental impacts of human activity – or environmental accounting [5-7]. Yet the connection between these three streams of research remains poor. The purpose of this paper is to introduce a new paradigm - the Planetary Accounting Framework – based on the Planetary Quotas, that will help bridge the gap between science, community, and policy with respect to managing the Earth System.

The Planetary Quotas are new metrics that represent the Planetary Boundaries but in terms of limits for human activity. Figure 1 shows how the three areas of Science (Planetary Boundaries), Community (Poly-Scalar Management) and Policy (Environmental Accounting) overlap to create the novel concept of the Planetary Quotas.

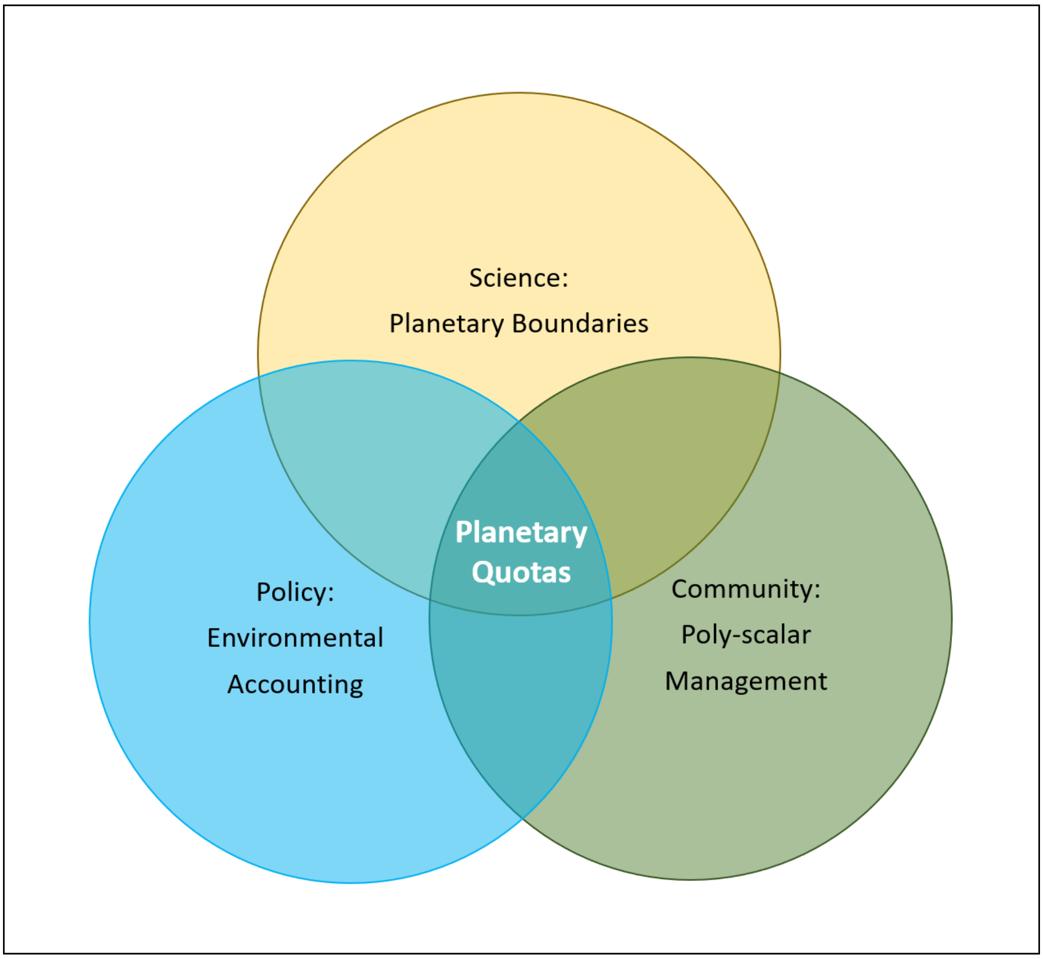

Figure 1: How the paper develops the Planetary Quotas and the Planetary Accounting Framework from the integration of science, policy and community.

The Planetary Quotas form the foundations of the Planetary Accounting Framework (PAF). The PAF is a framework that facilitates the comparison of any scale of human activity to global limits. As shown in Figure 2, this framework provides the platform (or bridge) for behavioural, policy, technological, and organisational change.

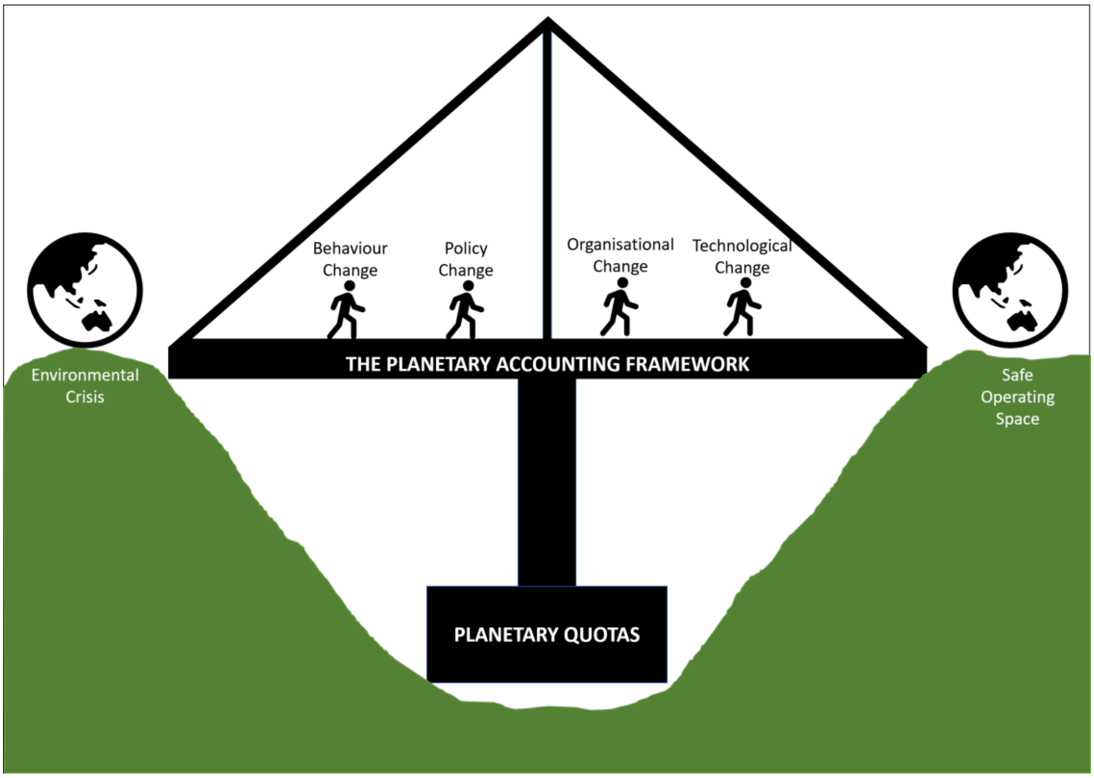

Figure 2: The Planetary Quotas provide the foundation for the Planetary Accounting Framework. The framework is the bridge that will enable change at all levels of human activity

The paper begins with an overview of the three theories shown in Figure 1. We then show how the Planetary Quotas can be derived from the Planetary Boundaries with an Appendix detailing how the Planetary Boundaries are now translated into Planetary Quotas. The final section describes the PAF and demonstrates how this can be used to shape policy and personal action. The paper ends with a discussion on the potential opportunities and constraints of the PAF and an overview of proposed future work on how to demonstrate the use of the PAF at all levels of human activity.

Theory 1: Planetary Boundaries: The Earth System Science of a planet with limits.

The sum of the planet's physical, chemical and biological processes is known as the Earth System. Everything in the Earth System belongs to one of four subsystems or "spheres": the geosphere, hydrosphere, atmosphere, and biosphere (land, water, air, life). The spheres are interconnected by Earth System processes (such as evaporation, transpiration, and photosynthesis) that store, transfer, and transform matter and energy according to the laws of physics [8]. These processes have complicated relationships with many feedback loops and tipping points that can lead to abrupt and substantial changes to the state of the planet as described by global and local ecological references [9, 10].

Climate change – a rapid change in global average temperature – is an example of such a process. As we emit more carbon into the atmosphere, we trap more heat. This increases average temperatures which leads to impacts such as melting icecaps. As the surface area of ice on the planet reduces, the average reflectivity of Earth's surface reduces. This means that more heat is absorbed. The risk is that we reach a tipping point – where the feedback loops positively reinforce one another – resulting in rapid and possibly irreversible warming, beyond our control.

Climate change can be considered a global environmental crisis. Most countries except the USA, Saudi Arabia and Nicaragua have now signed the Paris global agreement to work together to avoid exceeding this planetary limit. However, to reach this goal will require action at every level of human activity. Climate change is only one of many global environmental crises we are facing. The bigger concern, which encompasses all key global scale environmental crises, is that we are at high risk of departing from a Holocene-like state of the Earth System.

The Holocene is the period of time which began approximately 11,500 years ago. Homo sapiens evolved approximately 300,000 years ago, during the Pleistocene epoch [11]. The Pleistocene was a much less stable epoch than the Holocene, marked by abrupt temperature changes as can be seen in Figure 3. Homo-sapiens survived through two ice ages and a brief interglacial period much warmer than current average temperatures [12]. However, during this period, for more than 280,000 years, humans subsisted as hunter gatherers who moved to suitable areas where they could survive. The stable temperatures in the Holocene epoch saw the rapid development of humans from hunter gatherers to urban and agricultural settled societies [1, 13]. The state of the planet during the Holocene – henceforth referred to as a Holocene-like state – is the only environmental state of the planet in which we know settled societies can thrive[1, 13].

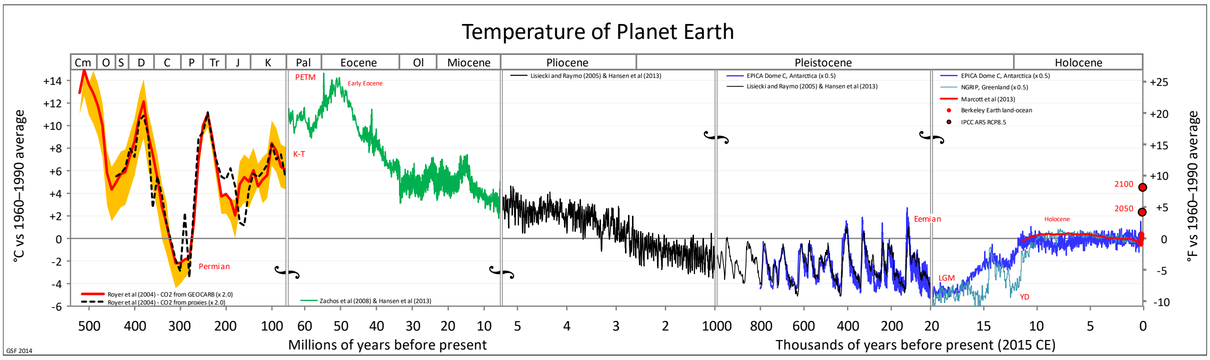

Figure 3: Average global temperatures on Earth during different geological epochs over the last 500 million years show the relative stability of the Holocene epoch (Source: [14])

Human influence on the state of the planet is now so substantial that a new epoch has been dubbed to acknowledge it, the Anthropocene[15]. The state of the planet during the Anthropocene is yet to be determined; it could be a Holocene-like state, or it could be a much warmer state. A warmer Anthropocene is unlikely to occur through gradual, linear change[16]. Predictions are for dramatic and likely irreversible change: substantial loss of species, devastating storms, significant sea level rise, and considerable displacement of communities [17].

There are external factors which could change the state of the planet that are beyond human control, for example, the strength of the sun, or the shape of Earth's orbit around it [18]. However, without human influence, the stable Holocene period would be expected to continue for at least several thousand more years [13]. Human activity over the next 50-100 years will most likely determine the state of the planet during the Anthropocene. It seems prudent thus that humanity should attempt to retain a Holocene-like state of the planet. This paper attempts to help by engaging human activity at all scales in this task.

Climate change is well understood in science and is being translated into policy action at all levels. However, the Planetary Boundary crisis goes far beyond the emission of CO_2 and other greenhouse gases (GHGs) into a complex set of interacting limits.

In 2009, 28 internationally renowned scientists identified nine critical Earth System processes that have limits beyond which the risk of departure from a Holocene-like state is high [13]. Some of the limits identified are associated with tipping points, others do not have tipping points themselves, but can impact other processes which do [13]. The critical Earth System processes, the control variables (environmental indicators) used to assess each process, and the preliminary limits for these variables – the Planetary Boundaries - are shown in Table 1. There is a level of scientific uncertainty as to the exact limits for each process. As such, the limits proposed have been set at a point where the risk of departure from a Holocene-like state is low [13]. Together these Boundaries define a "safe-operating-space" for humanity [13].

Table 1: Summary of the critical Earth System processes, corresponding control variables (environmental indicators), and preliminary Planetary Boundaries (limits) which together make up the "safe-operating-space" within which the risk of departure from a Holocene-like state is low.

Earth system process	**Control variable**	**Planetary Boundary**
Climate change	Atmospheric concentration of carbon dioxide Change in radiative forcing	≤ 350ppm ≤ 1W/m^2
Biodiversity loss	Global extinction rate	≤ 10E/MSY
Nitrogen and phosphorus cycle	Reactive nitrogen removed from the atmosphere Phosphorous flowing into oceans	≤ 62Tg ≤ 11Tg
Stratospheric ozone depletion	Stratospheric concentration of ozone measured in Dobson Units (DU)	≤ 5% below pre-industrial levels (290 DU)
Ocean acidification	Mean saturation state with respect to aragonite in the oceans	≥80% of the pre-industrial level
Fresh water use	Freshwater consumption	≤4000 km^3/yr
Change in land-use	Area of forested land as a percentage of original forest cover	≥ 75%
Novel entities	NA	NA
Atmospheric aerosol loading	Aerosol optical depth	NA Regional limit of ≤ 0.25

Notes:

- ppm stands for parts (of carbon dioxide) per million (parts of atmosphere)
- Radiative forcing is the change in energy flux in the atmosphere measured in Watts per square meter of Earth's surface area (W/m^2)
- Extinction rate is measured in the number of extinct species per million species per year
- Saturation state with respect to aragonite is an indicator of ocean acidity
- Aerosol optical depth is a measure of the fraction of sunlight that is absorbed or reflected – a value of 0 indicates perfectly clear skies – a value of 1 indicates no sunlight penetration

In 2015 we had already exceeded four of the Planetary Boundaries[2]. The situation is urgent. The risk of departure from a Holocene-like state is high unless human activity changes rapidly. However, these limits as stated do not translate into their significance for community and policy. The PB's refer to limits for Earth System processes rather than limits for human activity.

Theory 2: Poly-Scalar Management: An approach to managing the Earth System

The task of managing the Earth System is not simple. In the past, most theories on how best to manage shared resources (such as forests, fisheries, or the atmosphere) led to the conclusion that top-down governance or private management were the only effective options [3, 19, 20]. These theories were based on simple game theory that used the underlying assumptions that people would always act to maximise personal gain, regardless of the greater good [3, 19, 20]. The "tragedy of the commons" is that logic will drive humans to continue to overuse resources for immediate personal gains until everyone loses[3]. This approach does not do justice to how communities actually work and how social science now understands the way human activity can change [4, 21-24]. Cultures and communities are formed to enable broader goals to be pursued that enable more than individualistic gain. The question then is, how are broader goals, such as environmental values, made part of the thinking in individuals, communities and cultures?

Since the 1980s there has been a growing movement supporting the decentralisation of managing the environment. These theories are based on observed human behaviours rather than conventional game theory [4, 21-24]. In a background paper to the World Development Report for the World Bank, Ostrom [25] proposed a polycentric, multi-levelled approach for dealing with climate change. A polycentric order being:

> "*one where many elements are capable of making mutual adjustments for ordering their relationships with one another within a general system of rules where each element acts with independence of other elements*." [26].

Applying this to global environmental management means action at all scales, from the individual through to whole communities and cultures, both mandated and self-organised, that is not coordinated or controlled by a central body, but is based on a singular goal or set of goals, for example limiting global warming to 1.5°C. We have called this a poly-scalar approach to managing human activity within the Planetary Boundaries.

There are many studies which support this approach e.g. [22, 27, 28]. Top-down efforts are necessary, but are inherently difficult at a global scale, just as all management works better when it engages people in the required activities [29, 30]. Using the example of global efforts to manage climate change, there is ongoing debate as to the magnitude of emission reductions required, the methods and strategies to achieve emission reductions and or uptake of GHGs from the atmosphere, and the division of responsibilities and costs. Four decades after the first global conference on the environment, there are only now the beginnings of a global plan that provides an adequate response to today's climate crisis [31]. Significant steps forward have been made that show the decoupling of wealth generation from fossil fuels [32, 33]. This progress began before the Paris Agreement and can be attributed to the agglomeration of efforts at all scales of human activity [32-34].

The reasons that global management is insufficient in driving global change go beyond issues of political accord. Global environmental problems are typically caused by a multitude of actions which take place at a small scale [25, 35]. Household environmental impacts (including impacts of transport and upstream impacts of goods and services acquired by households) can account for as much as 70-80% of the economy's environmental loads [36]. Given the diverse nature of the causes of global issues, global or even national policies can miss local opportunities for emission reductions [27, 35]. People also tend to be more open to change implemented by local communities, businesses, organisations and authorities where plans have been developed with the specific community in mind, than to national level schemes [27, 35]. Although the literature on behaviour change shows mixed results there is powerful evidence that when design and technology are changed to make lower impacts the results can be positive [33, 37-39].

On the other hand, small-scale or local initiatives alone would be insufficient to manage a global problem such as climate change as many opportunities to reduce emissions rely on decisions which can only be made at a larger scale [35]. It is these poly-scalar approaches that lead to changes in design, technology, regulations, and hence behaviour [39] [38]. Thus, global management theory needs to be applied to Planetary Management and, in particular, the scale at which most people are engaged must be clarified.

Benefits of a poly-scalar approach to managing the Earth System include:

- the possibility for immediate action – rather than a need to wait for global accord,
- the facilitation of widespread experimentation and learning at multiple scales – rather than the need to determine an effective approach prior to rolling out global initiatives,
- the flexibility to encompass different centres of decision-making which are formally separate – creating a bridge that is necessary to achieve change [28], and most of all
- the ability to engage people in whatever scale of activity they can focus on.

Such an approach would likely help to resolve the many issues inherent in managing the shared resources and create opportunities for meaningful change in our Earth.

One might argue that there is already a poly-scalar approach to managing the Earth System underway. We agree that in the case of greenhouse gas emissions this is true. There are also current efforts at all levels to reduce broader human impacts on the environment. What is missing from the current approach is the "general system of rules" – the common goal for this multitude of activities. Targets for environmental initiatives range enormously, from those aiming for a very loosely defined state of "sustainability", to those working towards a circular economy, or others directing their efforts towards reducing their ecological footprint [5, 40-42].

Further, targets are almost always based on improvements to the status-quo or a past environmental state, rather than a desired future state founded in science [43]. Incremental improvements (as opposed to systemic changes) are criticised for their rebound effect [44-46]. Incremental improvements can also lead to missing opportunities for systemic change [43]. However incremental improvements are also the basis of most personal and policy change [33].

What is needed is a poly-scalar approach based on a set of critical global scientific limits which clearly define the end goal. Linking these two approaches, scale of action and limits, requires a new accounting approach – Planetary Accounting.

Theory 3: Environmental Accounting – Creating a shared empirical basis for different environmental issues.

Environmental Impact Assessment (EIA) – the quantification of environmental damage from human activity – was first formalised in 1969 at the United Nations Conference on the Environment in Sweden [47]. It was first introduced into government legislation the following year by the United States National Environmental Policy. By the early 1990s EIA was part of national legislation for more than 20 nations [47].

The translation of EIA into environmental accounting – the practise of measuring and monitoring environmental assets, gains, and losses over time - followed quickly. Norway was one of the first countries to begin formal environmental accounting. They identified their *environmental assets* – forests, fisheries, energy, and land and began to monitor and track these in the early 1980s [48]. The Netherlands introduced the National Accounting Matrix including Environmental Accounts in 1991 [49].[47, 50]

Today, environmental accounting is common practice for many businesses, cities, and nations and can also be done for individuals, groups of people, or products and services. Environmental Accounting encompasses a broad range of environmental monitoring and assessment. It includes State of the Environment reporting – the analysis and monitoring of environmental trends, through to product impact assessments – the estimation of impacts per unit of product produced. Impacts are estimated using EIA methods such as Life Cycle Assessment (LCA) and environmental footprint assessments and monitored over time. LCA refers to the assessment of all environmental flows which go into the production of a good or service – including upstream impacts such as the extraction of raw materials, and downstream impacts such as the final disposal of the product. The results of these assessments are very detailed and often hard to understand for a layperson. Environmental footprints typically assess a single environmental impact such as the amount of carbon emissions or land used for a certain activity or set of activities. Environmental footprints can also include upstream and downstream impacts. The calculation process varies between footprints but it is typically a less formal process than LCA. The benefit of footprint assessments is that the results are easily communicated to the general public e.g. the Ecological Footprint which calculates the number of planets to absorb an activity when multiplied by the number of people on the planet [5].

Environmental accounting represents a breakthrough in managing the impacts of human activity on the environment. It is now possible to estimate ahead of time with reasonable accuracy what the environmental impacts of a future activity are likely to be. Thus decision making, planning, policy and legislation can all be informed by such practises. Bottom up estimations of impacts enable relevant decisions to be made about human activity at appropriate scales.

The shortcoming of environmental accounting is that results of environmental assessments are typically reported against self-selected targets. Targets are often based on a percentage improvement from a previous reporting period, sectoral commitments (for example national commitments to meet carbon targets) or using sectoral or industrial benchmarks. Existing environmental assessment tools have been identified as lacking in suitability to inform society regarding environmental matters because of a lack of science based targets or limits [43, 51].

Carbon accounting (or GHG accounting) is the most widely used form of environmental accounting. The important difference between carbon accounting and other environmental accounting practises is that the results can be easily compared to global limits. This is one Planetary Boundary for which Planetary Accounting exists and is used in poly-scalar management.

There are debates as to a “safe” level of global warming and therefore maximum allowable CO_2 emissions. Nonetheless it is possible to translate a global target of average global warming in degrees Celsius, to a corresponding concentration of CO_2 in the atmosphere, and then to a maximum budget for anthropogenic CO_2 emissions. CO_2 emissions for an activity can thus be linked to a global budget based on scientific knowledge. Carbon accounting has led to widespread understanding of what is a relatively complicated scientific problem.

Individuals and communities can calculate their "carbon footprint" – the amount of CO_2 released due to the activities of the individual or community. Formal greenhouse gas accounting protocols have been developed for nations, cities, and products and services eg. [6, 52]. CO_2 emissions have been translated into dollar values. Studies have been completed to assess the relative benefits of a carbon tax versus carbon trading. Different approaches for managing emissions and different technologies for reducing emissions or absorbing carbon from the atmosphere have been trialled in different locations and at different scales allowing for a very rapid uptake of knowledge and development.

Carbon accounting is a remarkable example of how human activity can be engaged in poly-scalar management to begin to address the Planetary Boundary for the atmospheric concentration of carbon dioxide. There is a long way to go, but these efforts at every scale have led to some success. For the third year in a row, population and GDP have increased while global CO_2 emissions have remained constant or declined [32]. However, the same easy system is not available for the other Planetary Boundaries.

Applying Environmental Indicators and the DPSIR Framework

The global uptake of EIA and environmental accounting led to the development of increasing numbers of environmental indicators with which to measure different impacts on the environment. Selecting appropriate indicators for different assessments became a major topic of research in itself e.g. [53-55]. The question became how to bring different environmental impacts and causes into a framework to understand how to address them.

In response to this vast number of environmental indicators developed for environmental impact assessments, a system to categorise these was adopted by the European Environment Agency – the Driver-Pressure-State-Impact-Response (DPSIR) framework, detailed in Figure 4 [56-58]. The DPSIR framework not only enables the classification and therefore better understanding of indicators, it can also be used to translate indicators from one category to another as there is a causal relationship between each category [56]:

- *Driver* indicators describe human needs. Some examples of Driver indicators include kilowatt hours of electricity, kilometres travelled, or litres of fuel for transport.
- Pressures which result from drivers are flows to the environment. One Pressure indicator resulting from the Driver indicators listed is CO_2 emissions.
- *State* indicators describe the environment. State indicators provide a snapshot of the status quo. Comparing the current State of a given ecosystem to a previous State allows us to understand the influence of human activity on the environment. For example, the change of the State indicator which corresponds to CO_2 emissions – the concentration of CO_2 in the atmosphere – has allowed us to understand the ramifications of emitting CO_2. It is this sort of indicator that is commonly used in State of the Environment Reporting.
- *Impact* indicators describe the results of changing environmental States. For example, one of the Impacts of the increased concentration of CO_2 in the atmosphere is an increase in average global temperature. Another Impact is species extinctions.

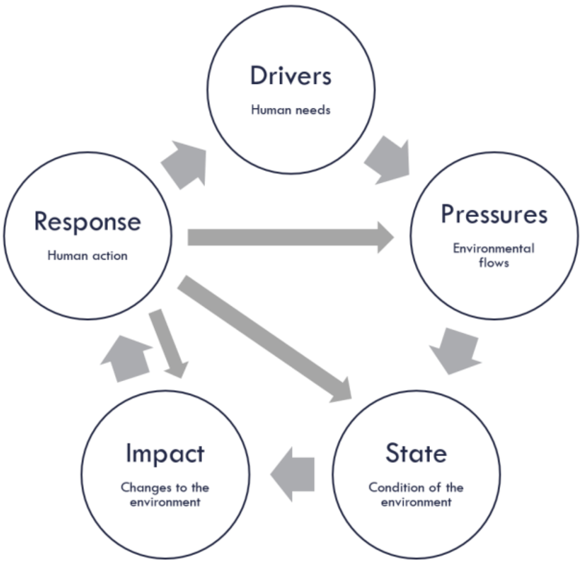

Figure 4: The Driver-Pressure-State-Impact-Response framework is a system of categorisation for environmental indicators. Indicators can describe human needs (Drivers), environmental flows (Pressures), the condition of the environment (State), or the changes to the environment (Impact). Each of these categories is linked such that Drivers lead to Pressures, Pressures determine the State, and a change in State is an Impact. Human actions (Responses) can target any level of indicator either directly or indirectly.

It was precisely this process of translating indicators from one DPSIR class to another that enabled the start of carbon accounting. In 2009 a target of maintaining global average temperature change to within 2°C was agreed as part of the Copenhagen Accord[59]. A change in global temperature, an *Impact* indicator, can be translated to a corresponding concentration of CO_2 in the atmosphere (a *State*) and then a global budget for maximum CO_2 emissions (a *Pressure*).

The State and Impact indicators in this set of indicators are very important it they provide insight as to the distance to target, the speed at which we are approaching, and the rate of change in the speed of the approach. However, they do not provide a useful mechanism for the development of policy, for decision making, or for behaviour. There is no straightforward way to divide the responsibility of the concentration of CO_2 in the atmosphere between different nations, cities, regions, or individuals. Nor can one directly compare specific human activities to the global average temperature. An individual deciding whether to take the car or the train to work, or a local government deciding whether to proceed with certain infrastructure – neither could begin to estimate the impacts of these decisions on the atmospheric concentration of CO_2. A different variable is needed to communicate the influence of human activity on the concentration of CO_2

It is only when these indicators are translated to the Pressure indicator – CO_2 emissions, that it becomes possible to begin to allocate this global budget between nations, cities, or any other level. It is also possible to calculate the emissions of CO_2, caused directly or indirectly by a specific activity, and compare these to the global (or any other) budget. This is the basis of carbon accounting. Through this approach, meaningful management decisions can thus be made at any scale of human activity.

The Disconnect between the Three Theories

Several authors have highlighted the opportunity for the Planetary Boundaries to reform environmental governance at multiple scales e.g. [28, 43, 60]. Several efforts have already been made to use the Boundaries for environmental accounting at different scales. For example, there have been several attempts to link the Boundaries to existing environmental assessment frameworks including footprint tools and life-cycle assessments [61, 62]. National targets have been developed based on the Boundaries for Switzerland, Sweden, and South Africa, and regional targets for the European Union and environmental accounting against these targets has begun [57, 58, 63].

The Boundaries as designed by the planetary scientists who first proposed them, were not intended to be disaggregated or scaled [2]. The purpose of the Boundaries was to provide a clear snap shot of the status quo of critical Earth System processes based on how these systems are measured globally. They do not define limits for human activity.

Each of the works adapting, or scaling the Boundaries and using these for environmental accounting used different approaches. For a true poly-scalar approach to managing the Earth System, there must be the flexibility for different approaches that are fit for purpose. However, in this instance, the result is huge variation between the control variables used in the applications, as well as the limits set. For example, the Planetary Boundary control variable for Biosphere Integrity is extinction rate (the number of extinctions per million species per year (E/MSY). In some adaptations, no control variable or limit was proposed to account for this Boundary. In others, an alternative control variable was proposed such as such as *biodiversity damage potential* (an estimation of species richness compared to background levels) [57] or *percentage of endangered and critically endangered ecosystems* [64]). These different control variables are not easily comparable to the original Boundary value and as such, the connectivity between the Boundaries and these attempts to implement them is reduced. Several of the Planetary Boundaries are not considered in any of the national or regional applications – for example the second Boundary for Climate Change - *radiative forcing* – and the Boundary for Atmospheric Aerosol Density – *aerosol optical depth.* Finally, the level of effort that has gone into each of the adaptations is high. It would not be practical for a poly-scalar approach to require such involved adaptations of global goals to each relevant scale of activity.

The DPSIR framework is used below to understand why the Boundaries cannot easily be scaled or used in environmental accounting as they are. Table 2 shows how each of the Planetary Boundary control variables fits into different DPSIR framework categories. There are 3 Pressure indicators, 5 State indicators, and 1 Impact indicator – rather than all being the same type of variable.

Table 2: This table shows the Driver-Pressure-State-Impact-Response (DPSIR) classification of the Planetary Boundary control variables (indicators).

Earth system process	**Planetary Boundary Control variable**	**DPSIR Category**
Climate change	Atmospheric concentration of CO_2 Change in radiative forcing	State State
Biodiversity loss	Extinction rate	Impact
Nitrogen and phosphorus cycle	N_2 removed from the atmosphere P flowing into oceans	Pressure Pressure
Stratospheric ozone depletion	Atmospheric concentration of ozone	State
Ocean acidification	Mean saturation state of aragonite in the oceans	State
Fresh water use	Freshwater consumption	Pressure
Change in land-use	Percentage of land cover converted to cropland	State
Novel entities	NA	NA

Atmospheric aerosol loading	Aerosol optical depth	State

For a poly-scalar approach to be applied to the Planetary Boundaries, a new set of Pressure indicators, which define the same safe-operating-space as the Boundaries, is needed. This can then enable us to link human activity to key global limits – the Planetary Accounting Framework.

The concept of Planetary Accounting builds on the concept of carbon accounting but enables the other Planetary Boundaries to be reduced to a similar kind of accounting framework. The Planetary Accounting Framework is based on the same set of global limits but they are reduced to a Pressure indicator that can be scaled. These we have called the Planetary Quotas. The Quotas represent the same safe-operating-space as the Boundaries but using indicators which can be directly compared to human activity at any scale.

Developing the Planetary Quotas

Several authors have identified the opportunity to use the DPSIR framework to determine a causal relationship between human activity and the Planetary Boundaries [57, 58, 65]. Two of the national adaptations of the Boundaries use a methodology based on the DPSIR framework [57, 58]. However, neither have applied it consistently across all the Boundaries to determine a series of scaleable variables.

We have taken this approach further. We have applied the DPSIR framework across the 9 Planetary Boundaries to determine global limits which are appropriate for use in a poly-scalar approach to managing the Earth System. We have taken care to use existing environmental indicators that are commonly used in present environmental accounting practises where possible. This is to enable straight-forward adaptation of past environmental accounts into the Planetary Accounting Framework.

Method for determining Planetary Quotas

Building on approaches used in past adaptations of the Planetary Boundaries, we have developed a methodology for the adaptation of the Boundaries to alternative control variables as follows:

1. Determine a list of critical pressures by:
    a) Disagregating each Planetary Boundary into corresponding environmental pressures based on the academic literature.
    b) Excluding pressures contributing less than 1% towards the corresponding Boundary (with a maximum of 5% of impacts excluded for any one Boundary).
2. Identify pressure indicators used in existing environmental assessment frameworks which correspond with one or more critical pressures by:
    a) In instances where existing indicators could be used for more than one pressure - assess whether the indicators were equivalent with respect to the corresponding PB(s) (i.e. whether reductions in one pressure could offset increases in another).
    b) Only grouping equivalent indicators.
3. Identify gaps in the availability of existing indicators to measure critical pressures.
4. Modify exisiting indicators or develop new indicators as required to measure these critical pressures.
5. Determine global limits (Quotas) for each of the selected pressure indicators based on all upstream Boundary indicators. These limits we based directly on the corresponding Boundaries (if straightforward) or on the academic literature (if complicated). Where

different upstream Boundaries yield different global limits, select the most stringent limit in order to ensure that all limits of the safe-operating-space were respected.

It is possible to further disaggregate Pressure indicators into corresponding Drivers. For example, the Pressure indicator - *CO_2 emissions* is the result of a multitude of different activities which can be measured using Driver indicators such as *litres of fuel used for transport* or *kilowatt hours of fossil fuel electricity consumed*. For any given Pressure, there are typically many Drivers. It is therefore simpler to use Pressure indicators than Driver indicators.

The Planetary Quotas

An Appendix sets out each of the Quotas in detail, including the scientific basis for the selection of each of the control variables and each of the preliminary limits. These are summarised in Table 3. Table 4 shows the current global status against each Quota.

The control variables for Carbon, MeNox (Methane and Nitrogen Oxides), Nitrogen and Water Quotas are all slight variations of existing footprint indicators. The Air Quality, Land, Phosphorous, Biodiversity and Ozone Quota control variables are all based on existing indicator concepts, but have all been proposed as new indicators by the authors for the purpose of the Planetary Accounting Framework.

Table 3: The Planetary Quotas

Planetary Quota	Control Variable and Global Limit	Description of Control Variable
Carbon Quota	Net carbon footprint ≤ -7.3 $GtCO_2$/yr	Total anthropogenic CO_2 emissions less total CO_2 withdrawn by humans from the atmosphere through reforestation, carbon uptake in soil, and engineered carbon sinks
MeNox Quota	Menox footprint ≤5.4$GtCO_2$e/yr	Total warming potential of methane and nitrous oxide emissions to the atmosphere expressed in terms of equivalent CO_2 emissions (CO_2e)
Land Quota	Deforestation footprint ≤ -11Mha/yr	Net forest land area transformed to or from forestland
Air Quality Quota	0.04 ≤ Air quality footprint ≤ 0.1	Air quality impacts of human emissions of aerosols and precursor gases expressed in equivalent aerosol optical depth (AODe)
Ozone Quota	Ozone footprint ≈≤0kgs/yr	Emission of gases controlled or due to be controlled under the Montreal Protocol in terms of total mass of emissions
Nitrogen Quota	Nitrogen footprint ≤62Tg/yr	Mass of reactive nitrogen released to the environment
Phosphorous Quota	Phosphorous footprint ≤11Tg/yr	Mass of phosphorous released to the environment
Water Quota	Net water footprint ≤8500km^3/yr	Net green, blue and grey water footprint*
Biodiversity Quota	Net biodiversity footprint ≤ 1E-4/yr	Net percentage disappearing fraction of species due to land occupation and transformation

* *green* = rainwater, *blue* =surface and groundwater, *grey* = the amount of freshwater required to dilute contaminated water to acceptable standards

The Planetary Boundaries are presented as distinct control variables with explicit limits. This is by design to make them easily communicable [2]. In reality, there is a high level of interconnectivity between the Boundaries. Thus, there is no linear, one-to-one relationship between the Boundaries and the Quotas. The connections between the two sets of variables are shown in Figure 5. The limits proposed for each of the Quota variables are based on the most stringent of the corresponding Boundaries. Interestingly, the Planetary Boundaries identified as “core boundaries” for their high level of interconnectivity – Climate Change and Biosphere Integrity [2], each correspond to more than half of the Quotas.

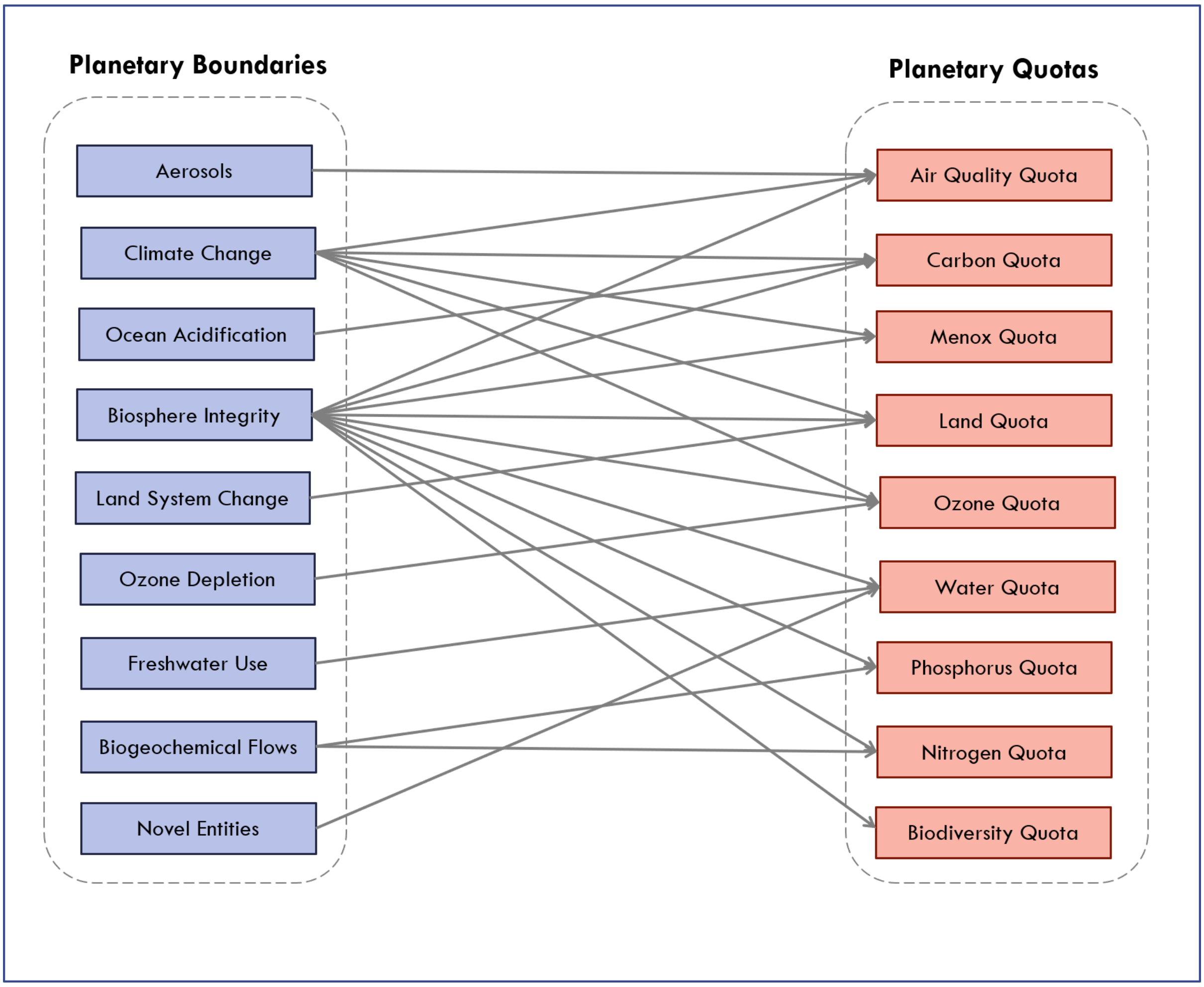

Figure 5: Each Quota corresponds to more than one of the Planetary Boundaries – there is not a linear one-to-one relationship between them.

In the latest update of the Planetary Boundaries the authors [2] show that five of the nine Boundaries have been exceeded, and that two have not been measured. Our estimates are also that five of the Quotas are currently exceeded, one is on the threshold, and the remaining two are uncertain. The current global estimates are shown against each Quota in Table 4.

It is important to note that exceeding a Quota is not equivalent to exceeding a Boundary. They are measuring different things. The Planetary Boundaries can be likened to health targets. When someone visits the doctor, they might have different bodily functions and processes assessed to assess their health blood pressure, heart rate, and weight. These values are compared to targets (or ranges) and based on this information, the doctor can determine whether the person is in good health or not, and, if not, which areas require the most focus.

The Quotas describe the actions that will improve or maintain a healthy state of the planet. In the example of human health, the doctor might suggest to a (healthy or unhealthy) patient that they maintain a healthy diet with a maximum intake of some foods, a minimum exercise regime, or an absolute reduction of cigarette consumption to zero.

In this way, the Quotas provide not only an annual target to return to a healthy environment, but also an indication of the direction of human behaviour with respect to the Planetary Boundaries. For example, we could be operating within the Carbon Quota for some time before we return to below the Planetary Boundary for atmospheric concentration of carbon dioxide.

It should be further noted here that unlike the Boundaries, no “zone of uncertainty” has been included for the Quotas. The zone of uncertainty is included in the Boundary framework to account for the fact that the science is uncertain. The Quotas are intended for use in policy, the design of technology, regulations, and behaviour. In keeping with the precautionary principle, we have thus set the Quotas according to the lower limits in the Planetary Boundary framework. Future work should include estimations of uncertainty around the Quota values.

Table 4: Each of the Planetary Quotas is shown against the estimate current global status showing five of the Quotas are currently exceeded, one is on the threshold, and the remaining two are unknown.

Planetary Quota	Limit	Estimate of Current Global Status
Carbon Quota	Net carbon footprint ≤ -7.3 $GtCO_2$/yr	~36 $GtCO_2$/yr [66]
MeNox Quota	Menox footprint ≤5.4$GtCO_2e$/yr	~11 $GtCO_2e$/yr *
Land Quota	Deforestation footprint ≤ -11Mha/yr	~6.5 Mha/yr [67]
Air Quality Quota	0.04 ≤ Air quality footprint ≤ 0.1	Data not available**
Ozone Quota	Ozone footprint ≈≤0kgs/yr	Data not available
Nitrogen Quota	Nitrogen footprint ≤62Tg/yr	~150 Tg/yr[2]
Phosphorous Quota	Phosphorous footprint ≤11Tg/yr	~22 Tg/yr[2]
Water Quota	Net water footprint ≤8500km^3/yr	~8500 km^3/yr***
Biodiversity Quota	Net biodiversity footprint ≤ 1E-4/yr	1E-5 – 1E-6/yr ****

*Derived from [66]

**In 2016, 92% of the world’s population lived in areas that exceed the World Health Organisation ambient air quality guidelines[68]. This suggests this Quota (which is based on these guidelines) has been exceeded.

***There is no indicator or limit proposed for the Planetary Boundary - novel entities. However, under the PQs this Boundary is addressed by proxy through the water Quota

****Based on background extinction rate of 100-1000 extinctions per million per year [2]

The Planetary Accounting Framework

The Planetary Quotas form the foundations for the new Planetary Accounting Framework (PAF). The PAF can be used to assess the impacts of any scale of human activity against planetary limits. For the first time, environmental impact assessments can be understood in the context of scientific limits at any scale. Figure 6 shows how the Framework can work for different scales and purposes.

The left-hand side shows the different mechanisms of the environmental impact assessment. The scope of activity to be assessed depends on the purpose of the assessment. For example, a city could consider either the impacts from all the activity that occurs within the city limits. Or the same city could consider all the impacts from the consumption of the city residents. As an example of how production and consumption accounting differ – one can consider a product such as clothing that is sold in the city but manufactured elsewhere. The manufacturing impacts would be included in consumption based accounts but would be excluded from production based accounts. On the other hand, the impacts of a product that was manufactured in the city and sold elsewhere would be included only in the production accounts. These are both valid and important assessments – but they give different information. This is why the purpose and scope must be considered together. Once the scope is determined, an environmental impact assessment can be carried out to determine the impacts in the Quota currencies (i.e. carbon, menox, water, etc).

The right side shows the poly-scalar aspect of the accounting. The Planetary Quotas can be scaled using any number of methods. Examples include an equal per capita share of the global Quotas, a grandfathering approach (the share of Quotas is determined by the share of current global impacts), or an economic approach (the share of Quotas is determined by the share of the global economy). These are just a few examples that are presented in more detail in the Discussion session. The scale and allocation procedure can be used to calculate the scaled limits in each Quota currency.

Finally, the results of the environmental impact assessment are compared to the scaled Quotas in a set of Planetary Accounts. The accounts show the impact and limit for each Quota currency, and thus the credit or deficit.

These accounts can then be used in any number of ways. They could inform policy and behaviour change, they could be used to compare impacts of different individuals, cities, products, or nations. They could be used as the basis for an international trading scheme.

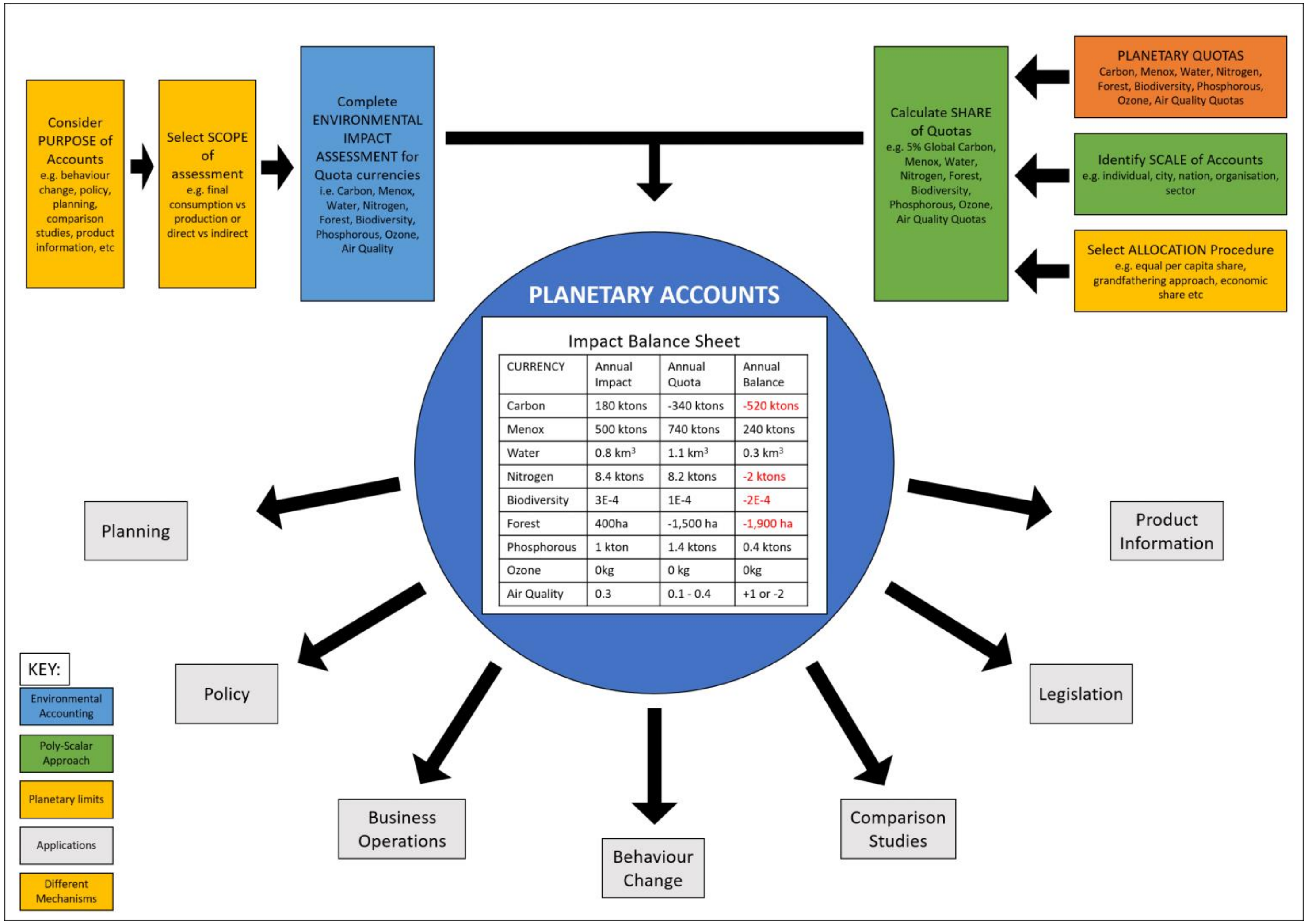

Figure 6: The Planetary Accounting Framework is a new paradigm for Earth System management. It is a novel system of comparing key results of environmental impact assessments with scientific global limits (the Planetary Quotas). The framework has different mechanisms for different scales or purpose to enable a truly poly-scalar approach to global management.

Discussion

Opportunities for Planetary Accounting in Practice

Planetary Accounting enables the scaling of global limits to limits at different scales to communicate an individual, city, company, or national share of the safe-operating-space. It is intended that the Quotas would be divided using an appropriate allocation procedure (see further discussion on allocation below) to determine national, city, sectoral, business, or individual Quotas. Environmental assessments could then be undertaken to compare the impacts of the nation, city, sector, business or individual to each scaled Quota.

Impacts of human activity can now be reported in key “environmental currencies” such as the mass of CO_2 emitted, the volume of water consumed, or the area of land appropriated for a given activity. Planetary Accounting is the framework which will facilitate the poly-scalar management of critical environmental currencies beyond CO_2.

There are many opportunities for applications of a Planetary Accounting framework. Individuals could compete with friends and strangers across the globe to live within their share of the planet’s limits through a serious game app. The same could be used by firms wanting to create a market for new design and technology products and services. City leaders could use the results of an environmental balance sheet as the basis for urban planning. Planetary Accounting could provide a scientific basis for the development of policy, governance models, and legislation at any scale.

We have not proposed a mechanism to compare one Quota to another or to amalgamate the results of environmental assessments into a single indicator of sustainability. This is intentional. The Earth cannot amalgamate these environmental currencies or trade one for another. If we consume too much water, this cannot be resolved by emitting less carbon, though it is appreciated that there is a nexus between water and carbon. At a global scale, each of the Quotas must be respected if we are to operate within the Planetary Boundaries. This does not preclude the opportunity to trade in each of the Quota currencies at lower scales. On the contrary, Planetary Accounting provides an opportunity for a global trading system for key global environmental “currencies” and in the process firms can see how these parameters interact and are synergistic. Moreover, the real costs to humanity of exceeding planetary limits – i.e. the costs of adaptation and mitigation – or the value of undershoot – i.e. the money not spent because nature provides a service - could be used to assign a monetary value to each environmental currency, for example $X / kg of nitrogen. Such an exercise could facilitate the incorporation of the environmental impacts into existing global economic frameworks thus enabling a further developing of wealth creation and environmental footprint [33].

To facilitate better producer and consumer responsibility, a product labelling system similar to the nutritional facts labelling system for food could be developed based on the Quotas. Whether this was displayed on products as part of a labelling system, or simply made available online, companies could use such a system to communicate the impacts of goods and services in different environmental currencies. A global labelling scheme could provide an opportunity to address the regional variation of some Quotas (such as the water Quota), discussed later.

Further work would be required to determine the appropriate format, inclusions, and exclusions for a labelling system such that it could be both accessible to a wide audience, and implementable for producers.

Allocating Quotas – A question of policy and ethics

The Planetary Quotas resolve the mathematics of scaling global limits to compare to different levels of human activity. However, they do not resolve the political and ethical dilemma of allocating the Quotas. Resolving the issue of allocation goes beyond the scope of this paper. However, the concept of Planetary Accounting cannot be presented without some discussion on the allocation of global quotas.

The concept of allocating resources has been most widely researched and debated with respect to the allocation of a global carbon budget e.g. [69-80]. Some of the most commonly discussed allocation procedures include:

- Equal per capita share – each person on the planet has an equal right to the resource,
- Grandfathering – rights to the resource are based on past use of the resource,
- Contraction and Convergence – high users reduce use of impacts while low users increase, until a certain point of convergence at an equal per capita share, and
- Common but Different – rights to the resource based on level of development.

The Planetary Accounting framework should have different mechanisms at different scales for different responsibilities and abilities to achieve outcomes.

For such a flexible approach, allocation would also need a high degree of flexibility. A Quota for the basis of self-organised initiatives is likely to be self-selected. Global negotiations for national commitments to Quotas are likely to be heavily influenced by politics. Private organisations may agree sectoral approaches to Quotas, may self-select Quotas as part of an internal sustainability strategy, or may be allocated Quotas by local authorities or company managers.

One of the greatest debates around the allocation of a global carbon budget is that historic emissions come from the same total budget as future emissions. This is not the case for every Quota. Most of the Quotas are based on annually renewing budgets not a fixed budget over time, for example the Water Quota is based on net annual water consumption [81] – thereby altering the frame of the problem.

Accounting Procedures

For Planetary Accounting to be used in a poly-scalar approach to managing the Earth System it must have a high level of flexibility in the way it is applied with different mechanisms at different scales and for different purposes.

There are two primary methods for determining which impacts to include in an environmental assessment – *consumption* or *production* impacts. The results of these two methods can differ greatly depending on the situation. For example, in national GHG accounts, a *production* calculation would include all GHG emissions resulting from activities taking place within the country under assessment. In contrast, a *consumption* calculation would take into account all GHG emissions associated with the consumption of the people residing in the country – regardless of the location of the emissions themselves. Both methods are valid but careful consideration is needed to select the most appropriate method in each situation to avoid misleading information. For example, if using the production method to estimate greenhouse gas emissions for a country, it does not make sense to then divide these results by the number of inhabitants in that country. Net exporters are likely to have higher per capita emissions than net importers. This information does not provide any insight as to the impacts of the activities of the countries' inhabitants.

For example, in Sweden the emissions produced within the Swedish borders has reduced from 72.7 million $tCO2_e$ in 1990 to 66.2 million tons in 2010 (Swedish EPA, 2012a). However, when they calculated the emissions corresponding to the consumption of the inhabitants of Sweden, the results were 76 million in 1990 and 95 million tons in 2003 (Swedish EPA, 2010). The production accounts showed a decrease in emissions but the consumption accounts showed an increase. Both sets of accounts provide useful but different information.

Beyond determining whether a consumption or production method of scope definition is selected, the specific scope of assessments (i.e. the impacts considered for a given activity) will need to be carefully defined so that assessments can be compared across industries and locations. Future work in this area should include the development of formal Planetary Accounting procedures and possibly independent review or certification standards.

The Quotas are a Moving Target not a Static Value

The Earth System is dynamic and the rate of increase in scientific understanding of its processes and limits is high. There is not time to wait until we have a perfect understanding of the system or its limits before we take action to operate within these – this may never eventuate. The indicators and limits presented in this paper are intended to be preliminary. It is our intention that, like the Planetary Boundaries, these are subjected to scrutiny, discussion, and analysis, and are regularly reviewed and updated over time as we advance in our collective knowledge and understanding.

Global vs Regional Limits and Impacts - An Issue of Scale

Carbon emissions are fundamentally different to most other planetary limits. Greenhouse gases have a long atmospheric lifetime and become well mixed in the atmosphere. This means that it is of little importance where the gas is emitted. 1kg of CO_2 will have the same contribution to global warming wherever it is released.

When we consider other limits, for example water consumption or the release of nitrogen into the environment, it is not the case that 1kg consumed or released in one location will have the same impacts as 1kg consumed or released elsewhere. If we take a few thousand litres of water from a water source with abundant supply, the local impacts are likely negligible. Taking just a few litres from another, water poor source, may have disastrous local effects. The release of a kg of nitrogen in a sparse agricultural area will have less impact on the Earth System than in an intense agricultural zone with risks of ground water contamination.

One way to include regionality in Planetary Accounting could be through a product and services labelling scheme as identified previously. To give an example of how this could work, a binary water scarcity indicator (yes/no) could be reported alongside the net water footprint to convey the suitability of the water source. In the same vein, regional issues for other environmental currencies could be included in such a system – the release of aerosols has more impact in highly populated areas or areas that already suffer from air pollution, than in areas where the air is clean. This information could also be included in a product labelling system.

In a similar manner, it would be interesting to explore the use of a binary efficiency indicator against a given benchmark. This would help put the raw environmental currency data into context for consumers. A tick or star system could be used to convey whether the results are better or worse than similar products.

Planetary Accounting is not intended as the one super-system to resolve all environmental problems though it will contribute to most. The purpose of Planetary Accounting is to allow humanity to manage human activity such that it does not push the Earth System into a new geological state.

There are many local environmental problems that do not translate into planetary limits. Land instability and polluted waterways due to poor farming practices, light pollution, urban heat island effects. Planetary Accounting does not replace local environmental management practices created locally and solvable locally; these must be dealt with at a local level.

This does not mean that regionality should be ignored. Regionality might be included in reporting planetary impacts through testing in demonstrations at different scalar levels appropriate to each of the Planetary Quotas.

Timeframe

The Quotas represent the same safe-operating-state as the Planetary Boundaries – as such they refer to an end goal rather than a pathway of reductions. The purpose of the Quotas is to allow humanity the freedom and flexibility to determine the best way to operate within the safe-operating-space. There is no specific date before which the Quotas must be respected. At any time that any of the Quotas or Boundaries are not respected, humanity is at risk of an irreversible departure from a Holocene-like state.

Conclusions

Humankind has the scientific knowledge needed to manage the state of the environment such that the Anthropocene is regenerated and helps recreate a Holocene-like state of the environment. There is evidence that a poly-scalar approach is the most effective mechanism to manage the global commons through engaging all levels of human activity. Environmental accounting has advanced to the point that we can estimate with reasonable accuracy what the environmental impacts of an activity are or will be. These three theories are advanced in the literature but are disconnected from one another. The Planetary Accounting Framework, based on the new Planetary Quotas brings these three theories together to enable poly-scalar management of the Earth System.

Planetary Accounting is a novel framework that could facilitate an unprecedented, global, multi-scaled approach to managing the Earth system. It needs to be trialled at all levels of human activity and further research can help show how to apply it in many different ways.

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