School of Design and Built Environment
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Planetary Quotas and the Planetary Accounting Framework
Comparing Human Activity to Global Environmental Limits

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This thesis is presented for the Degree of

Doctor of Philosophy

of

Curtin University

November 2018

DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Date: …21st November 2018…………..

ABSTRACT

Human activity is altering environmental processes to the extent that we are at risk of changing the state of the planet from one that is hospitable to humanity to one that is potentially hostile. The Planetary Boundaries are global environmental limits derived from Earth system Science that together define the "safe operating space". Within the Planetary Boundaries, the risk of changing the state of the planet is low but already four of the Planetary Boundaries have been transgressed. There is an urgent need to manage human impacts on the global environment so that we can return to the safe operating space.

Policy makers and scientists want to use the Planetary Boundaries to manage human impacts on the environment so that we can return to the safe operating space. However, the Planetary Boundaries were not designed to be scaled or compared to human activity. There is a need to translate the Planetary Boundaries into a framework that is accessible and actionable.

This thesis develops the concept of Planetary Accounting using Planetary Quotas to achieve this goal. It uses three key theories to resolve the issue:

First, management theory showed how to relate change in the commons to a poly-scalar approach. Second, from accounting theory was the understanding that standards and limits are needed if a realistic approach to achieving human change is being sought. Third, from environmental accounting theory there are different categories of indicators - Drivers, Pressures, States, Impacts, and Responses – and only if indicators are uniformly in the Pressure category can human activity be related to a limit and scaled accordingly.

Thus, environmental accounting mechanisms were used to translate the detailed Earth system Science in the Planetary Boundaries to create 9 Planetary Quotas – limits for human activity in "environmental currencies" such as carbon emissions, water consumption, nitrogen use, and aerosol pollution. A high-level Planetary Accounting Framework provides the mechanism to scale these indicators, the Planetary Quotas, and compare them to any scale of human activity.

Planetary Accounting allows meaningful decisions to be made at any level or sector regarding policy, planning, technology, business operations, legislation, and behaviour. It could enable the incorporation of the economic value of environmental impacts and management into existing global economic structures. Planetary Accounting enables the practical application and communication of the Planetary Boundaries to all scales of human activity.

Dedicated to my children Patrick and Hazel.

I hope that we manage to hand over a healthier planet to your generation.

ACKNOWLEDGEMENTS

First and foremost, I would like to acknowledge my supervisor Professor Peter Newman. Peter has believed in the potential of this project from the outset and has helped me to persevere even when I felt I had taken on more than I could manage. Peter was the inspiration for my research field trip which added more to depth to my research than I could have fathomed. He has provided enormous insights and encouragement throughout this project and I couldn't have completed this journey without him.

Secondly, I would like to express my huge gratitude to my husband Owen who has supported this project in so many different ways. He encouraged me to take on the project even though we had just had our first child when I started. He has taken substantial time out from his own career to look after our children to support my research. He has also been an amazing sounding board for my work, helping me to break down and move past many obstacles in my research and thinking.

I would also like to give particular thanks to:

My dad Alan and brother Mikey for the many hours they have spent reviewing my work and the many insights they have both contributed;

My mum Sally for all her hours of babysitting to allow me to write up my thesis;

My brother David for his endless support, advice and encouragement;

Greg Morrison for his early direction on how to approach an effective literature review;

Christine Finlay and Imran Khan for all their administrative support which was always done with such warmth and speed; and

Friends and family who have given me so much support and encouragement along the way – with particular thanks to Roxanne Butters, David and Christine Campbell, Katie Brown, and Zoe Sizemore.

During my fieldtrip I met so many people who contributed so much to my work, and I would like to thank all who spent the time to hear about and discuss my project. In particular I would like to acknowledge the insights and encouragement from Will Steffen, Katherine Richardson, Johan Rockström, Sarah Cornell, Andreas Hauser, Arjen Hoekstra, Ashok Chapagain, Morten Ryberg, Michael Hauschild, Dieter Gerten, Wolfgang Lucht, Albert Bleeker, Jan Willem, Harry Wilting, Detlef van Vuuren, Paul Lucas, Alessandro Galli, and Paulo Magalhães

Thank you also to APA, CUPSA, and AuDA who supported this research.

There are so many other people who have supported and encouraged me on this journey and I am so grateful to them all.

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INTRODUCTION

1.1 The Journey

In 2009, twenty-eight internationally renowned Earth system scientists led by Johan Rockström at the Stockholm Resilience Centre (Rockström et al., 2009a) developed the Planetary Boundaries (PBs) – critical global environmental limits that define a “safe operating space” for humankind. If human activity pushes the planet beyond these limits, we are at risk of changing the state of the planet. The general environmental conditions that can be associated with life over the last 10,000 years is the only state in which we know humanity can thrive. The alternative state is unknown, but it is likely to be hotter, less stable, and less favourable to humankind. In 2009, three of the PBs had been transgressed, the PBs for climate change, biogeochemical flows, and biodiversity loss. In 2015, the PBs were updated (Steffen et al., 2015). By this time a fourth PB had been transgressed, the PB for land use. The message from the PBs is clear. We are living beyond Earth’s environmental limits. The risk that human activity could fundamentally change the state of the planet is high. We ought to manage human activity such that we can live well within the Planetary Boundaries. The problem is how?

The PBs convey important information about the health of the planet. However, they are not accessible or actionable. Scientists and policy makers want to try to translate the PBs into policy, to use them as the basis for managing human impacts on the environment. But, the PBs were not designed to be used in this way. They were intended as Earth system science indicators of the extent and urgency of the problem. They are not a guide to resolving it. Regional and national environmental targets have been developed using the PBs as guidance and scientists have established frameworks to try and link the PBs to environmental accounting systems. However, each of these works have severe limitations, both in their connectivity to the PBs, and in their applicability to environmental management. They just don’t relate simply to human activity or to different levels of government.

Herein lies the basis of this research. How can the PBs be translated into a framework that is accessible and actionable? How can they be used to help us manage human impacts on the planet so that we could return to and live within the safe operating space?

This thesis will set out how to do this through three key discoveries that led to the eventual solution and which will be expanded in much greater detail in the thesis. The first discovery came from management theory. Current environmental management practices are often through top-down governance or private management. These practices are based on out of date theories of environmental management such as the tragedy of the commons – the concept that, in the absence of enforced rules, humans are unable to share resources (such as forests or fisheries) without overusing and exploiting them. The more recent findings in the fields of behaviour change, commons management, and change theory can be used to show that a more effective approach would be a poly-scalar one. This can be defined as one which applies across different levels of human activity, from the bottom up as well as the top down, which can be implemented through government, private institutions, and self-organised management, and which is coordinated by a general system of rules with different mechanisms at different centres of activity.

The second key discovery was a critical insight from accounting theory that only if there are standards or limits can you create serious change. Humans have become very good at estimating past, present, and future environmental impacts from human activity. The ongoing measurement and monitoring of environmental assets (for example, forests, land, or fisheries) and of our impacts on these is called environmental accounting. It is now common for businesses, cities, and nations to keep environmental accounts – to track environmental impacts and the state of environmental assets over time against targets and benchmarks. Environmental accounting is an important tool for helping humans to reduce our impacts on the planet as it can be used to inform decision making at any scale of activity. However, the key limitation is that for most impacts, there is no clearly determined end goal, no standard, no limit. Targets for maximum impacts are typically set based on percentage reductions from a current or past status quo, or on industry best practice. Such targets are arbitrary. They are also exhausting. There is a seeming need to endlessly reduce impacts. Environmental problems seem insurmountable and never ending. There is a need to quantify the end goal based on the scientific environmental limits of the planet.

The third, and perhaps the most important discovery that informed this research came from theories about indicators, that different types of environmental indicators serve different purposes. The European Environment Agency developed a framework to categorise environmental indicators, the Driver, Pressure, State, Impact, Response (DPSIR) framework (EEA, 2005). Any environmental indicator can be classified as either a Driving force (a human need, such as the need for fuel), a Pressure (a flow to the environment, such as CO_2 emissions), a State (describing the state of the environment, such as the concentration of CO_2 in the atmosphere), an Impact (describing a change in State, such as global warming), or a Response (describing a human response to the environment, for example the Paris Agreement).

Human activity directly influences Drivers and Pressures, but only indirectly influences States and Impacts. Both types of indicators are important, but they serve different purposes. State and Impact indicators communicate the status quo. Pressure and Driver indicators communicate action. The problem with the PB indicators is that they are not all in the same DPSIR category. Three of the PB indicators are Pressures, five are States, and one is an Impact. The PBs given in State and Impact indicators give an overview of planetary health. They communicate information such as that the concentration of CO_2 in the atmosphere and the rate of species extinctions are too high. The PBs given in Pressure indicators are limits for human activity. They communicate what we can do, for example how much fresh water we can consume, or how much nitrogen we can fixate.

As we need limits to set the standards for change, the result is that we need to define critical Pressures and limits for these. Then we can begin to generate something that human activity can relate to. Some of the PB indicators, the Pressure indicators, are accessible and actionable. They can be scaled, divided, and compared to human activity. However, the majority of the PB indicators, the State and Impact indicators, are not. It is not straight forward to allocate responsibility for global species extinctions, or to compare the lifestyle choices of an individual to the atmospheric concentration of CO_2.

The insight that the PB indicators are of varying DPSIR categories is not new though it was not communicated to those in the Earth system science arena who could not see the way ahead to change human activity. The first attempt to translate the PBs into policy was the development of national targets for Sweden (Nykvist et al., 2013). The authors identified that humans can directly control Drivers and Pressures, but not States or Impacts. Further, they highlighted that the PB indicators were not all of the same DPSIR category. Their proposed approach was thus to translate the PBs into Pressure indicators. However, they only achieved this for one of the PBs, the PB for CO_2 concentration. They did not translate the remaining State and Impact PB indicators into limits for Sweden. A later adaptation of the PBs to targets for Switzerland also references the variance in the PB indicator classifications. However, the indicators selected for Switzerland in this study also vary between DPSIR categories. No one has previously translated the full set of PBs into Pressure based indicators. Each of them have particular issues with their methodology for deriving the quota as will be set out in the thesis. There is likely to be other attempts at how these are done but at least in this thesis there is set out a way of attempting to make an actionable and accessible indicator or quota that is scaleable and thus can be applied to human activity.

The Planetary Boundaries and the three insights described above form the basis of the research presented in this thesis which attempts to address the following research questions.

1.2 Research Questions

The primary question is:

How can we connect leading scientific theories of the Earth system and global limits with leading theories of change management and environmental accounting to develop an implementable system of planetary management?

To answer this primary question, the following secondary questions need to be addressed:

1. Can humans actually change the state of the planet?
2. What is the Earth system Science of Planetary limits?
3. What is the best way to manage the global environment?
4. How can environmental accounting be used to manage human impacts on the global environment?
5. Why is it difficult to translate the Planetary Boundaries into policy and action?
6. How can these three fields of research, Earth system science, management theory, and environmental accounting practices, be brought together to create scalable environmental quotas that can enable change in human activity? and
7. How can environmental quotas be applied in a robust and transparent framework to allow human activity to be managed within the safe operating space of the Planetary Boundaries?

1.3 Planetary Quotas and the Planetary Accounting Framework

To answer these questions, this thesis introduces a new set of global limits, based on the PBs, but using Pressure indicators, the Planetary Quotas (PQs). The PQs bring together the insights from the three fields of research described in Section 1.1 by connecting the Planetary Boundaries and environmental accounting in a way that can be used at any scale using the DPSIR framework (see Figure 1).

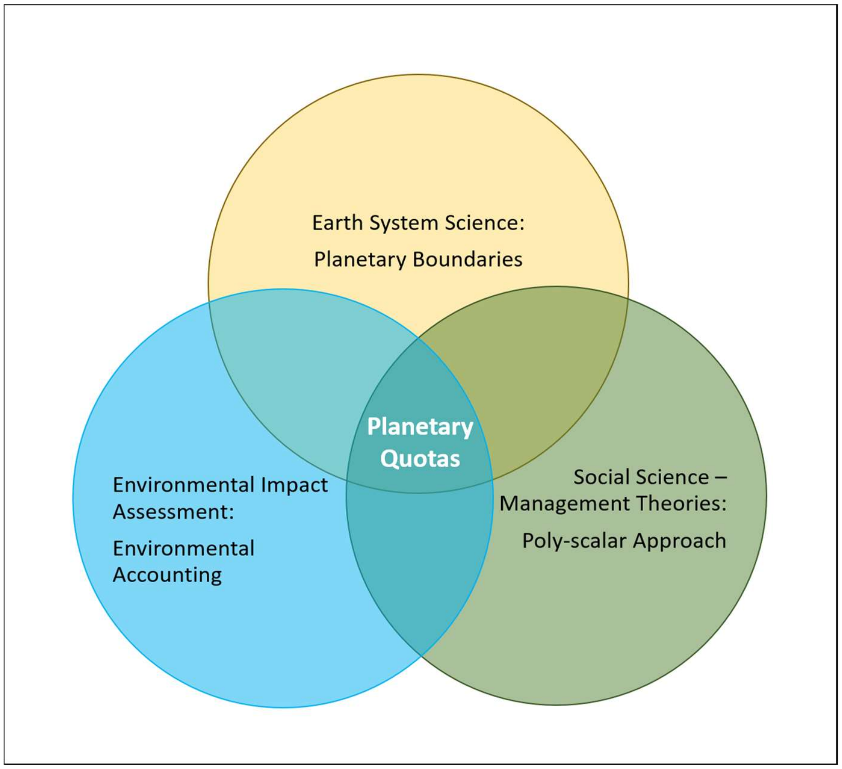

Figure 1: The novel Planetary Quotas bring together the latest advances in Earth system science (the Planetary Boundaries), environmental impact assessment (environmental accounting), and the social science of management theory (poly-scalar management)

The PQs create the foundation for a new concept - planetary accounting – comparing the results of environmental impact assessments to global scientific limits. A high-level Planetary Accounting Framework (PAF) shows how the PQs can be applied to any scale of human activity to provide a platform for change from environmental crisis to the safe-operating-space (see Figure 2).

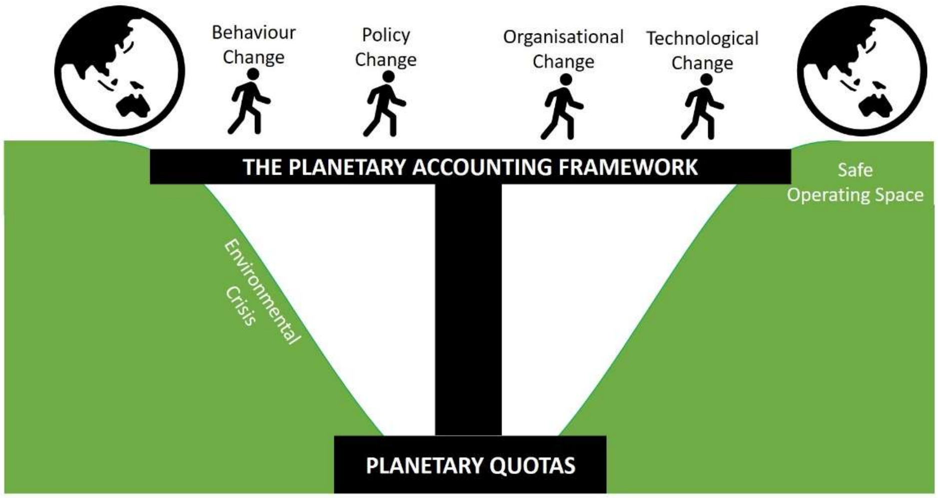

Figure 2: The Planetary Quotas form the foundations of the Planetary Accounting Framework - a bridge for change.

1.4 A Guide to this Thesis

The thesis has been laid out in the style of a series of individual papers or chapters that together make a coherent approach. Thus, each chapter has an abstract and conclusion. This is the style that is used by many publishing houses now to enable each part to be available for on-line purchase as a separate academic publication or for the reader to choose a series of such chapters rather than the whole collection. It is appropriate for my research because of the breadth of topics that need to be addressed to explain the Planetary Quotas and to outline the Planetary Accounting Framework.

The overall structure of the thesis is as follows:

- Introduction
- Section 1 – Literature Review
- Section 2 – Methods
- Section 3 – Results
- Conclusions

Section 1 is a review of the literature. It describes the background to the research and identifies the gap in the literature this thesis aims to address. Section 1 is divided into five chapters:

- Chapter 2 – The science of anthropogenic climate change

The research presented in this thesis is based on the assumption that human activity can change and is changing the state of the planet. In recognition that not everyone believes that this assumption is true, this chapter presents the scientific evidence that supports this theory, and addresses the key arguments made against it.

- Chapter 3 – The Holocene, the Anthropocene, and the Planetary Boundaries
  This chapter presents past attempts to define the limits for human impacts on the planet. It identifies some of the challenges people have faced in determining global limits and shows why the Planetary Boundaries framework is the most robust and advanced definition for global limits at this point in time.

- Chapter 4 – Managing the Earth system – why we need a poly-scalar approach
  This chapter provides an overview of past and present theories of how best to manage shared environmental resources and of how to generate change. It concludes with the proposal that a poly-scalar approach is needed to manage the Earth system.

- Chapter 5 – Environmental Accounting, Absolute Limits, and Systemic Change
  This chapter provides a historical account of environmental impact assessment methods and environmental accounting practices. It shows that a key limitation of most environmental accounting is that the impacts of human activity determined through environmental impact assessments cannot be compared to scientific limits. It demonstrates that absolute, scientific limits, are likely to be a key component to achieving systemic change.

- Chapter 6 – Resolving the disconnect between Earth system science, environmental management theory, and environmental accounting
  This chapter shows how the DPSIR framework from environmental accounting can be used to show why the Planetary Boundaries are not accessible or applicable to human activity. It concludes that key constraint for using the Planetary Boundaries is that they are not all of a single DPSIR category and that in order to make them accessible, they should be translated into a uniform set of Pressure category indicators.

Section 2 is a detailed description of the methodology and methods used in this research project. This section comprises a single chapter:

- Chapter 7 – Translating the Planetary Boundaries into Planetary Quotas
  This chapter provides a high-level introduction to the Planetary Boundaries and Planetary Quotas. It then describes the overall methodology for the project, the methods used to translate the PBs into PQs, and the framework used to derive specific PQs.

Section 3 describes the results of the research. The first nine chapters in this section give a background to each of the Planetary Quotas and describe the methods and scientific basis for each. The final chapter concludes this section by bringing the Planetary Quotas together into a full set of limits and showing how these can be used in the Planetary Accounting Framework.

- Chapter 8 – A Planetary Quota for Carbon Dioxide
  This chapter presents the background and need for a Planetary Quota for carbon dioxide and shows the detailed methodology used to derive this.

- Chapter 9 – A Planetary Quota for Methane and Nitrous Oxide
  This chapter presents the background and need for a Planetary Quota for methane and nitrous oxide and shows the detailed methodology used to derive this.

- Chapter 10 – A Planetary Quota for Forestland
  This chapter presents the background and need for a Planetary Quota for reforestation and shows the detailed methodology used to derive this.

- Chapter 11 – A Planetary Quota for Ozone Depleting Substances
  This chapter presents the background and need for a Planetary Quota for ozone depleting substances and shows the detailed methodology used to derive this.

- Chapter 12 – A Planetary Quota for Aerosols
  This chapter presents the background and need for a Planetary Quota for aerosols and shows the detailed methodology used to derive this.

- Chapter 13 – A Planetary Quota for Water

This chapter presents the background and need for a Planetary Quota for water and shows the detailed methodology used to derive this.

- Chapter 14 – A Planetary Quota for Nitrogen

  This chapter presents the background and need for a Planetary Quota for nitrogen and shows the detailed methodology used to derive this.

- Chapter 15 – A Planetary Quota for Phosphorous

  This chapter presents the background and need for a Planetary Quota for phosphorous and shows the detailed methodology used to derive this.

- Chapter 16 – A Planetary Quota for Biodiversity

  This chapter presents the background and need for a Planetary Quota for biodiversity and shows the detailed methodology used to derive this.

- Chapter 17 – The Planetary Quotas and a Planetary Accounting Framework

  This chapter brings the Planetary Quotas together as a suite of global limits for human activity and shows how these can be used by outlining a high-level Planetary Accounting Framework to inform many different aspects of human activity

The thesis finishes with a final section and chapter – Conclusions and Future Work:

- Chapter 18 – Conclusions and Future Work

  This chapter shows how I have addressed the research questions laid out in this introductory chapter. It outlines the key strengths and weaknesses of the research project and identifies areas of future work.

1.5 Publications

The concept of the Planetary Quotas has been published in a chapter of a book and an overview paper has been accepted for publication in the new Springer-Nature-BMD journal *Sustainable Earth:*

> Meyer, K., and A Merry. 2017. "Saving Civilization through Personal Budgeting in a Quality Improvement Paradigm." In *Statistics, Science and Public Policy XXI*, edited by AM Herzberg. Herstmonceux Castle, Hailsham, UK: National Library of Canada Cataloguing in Publication.
>
> Meyer, K. and Newman, P. 2018. Planetary Accounting – A Quota-based approach to managing the Earth system. *Sustainable Earth* (1).

SECTION 1

CHAPTER 2

The science of anthropogenic climate change

Abstract

There is scientific evidence to suggest that human activity, in particular the release of greenhouse gases to the atmosphere, is currently causing the climate to warm up. A warmer climate is predicted to be unfavourable for humanity. However, there are some people who dispute the theory of anthropogenic climate change, arguing either that the climate is not changing, that the change is not caused by human activity, or that it is not important.

Data taken from multiple sources shows a clear warming trend since pre-industrial times. 2016 was the hottest year on record. Average temperatures are now more than 1°C higher than during pre-industrial times.

Greenhouse gases trap shortwave radiation and therefore heat into the atmosphere. Approximately equal quantities of greenhouse gases are emitted and absorbed naturally every year. Human activity releases a relatively small amount of greenhouse gases to the environment compared to natural processes. However, we absorb very little of what we emit. Thus, there is a net flow of these gases to the environment from human activity.

There are no natural factors which correlate with the current warming trends. The primary theory for natural warming is that it is caused by changes in the solar cycle. However, the amount of energy coming from the sun has been reducing since 1980 and warming has continued.

There have been higher levels of greenhouse gases in the atmosphere before and life has flourished. However, this has been during stable climate conditions. Rapid increases or decreases of greenhouse gases in the past have been highly destructive to life on Earth.

It is extremely likely that the climate is changing because of human activity. This is expected to mean less favourable conditions for humankind.

2.1 Introduction

The debate between climate change advocates and climate change sceptics in the media is prolific and heated. Advocates and sceptics call one another "deniers" and "alarmists". Both sides frequently use the term "myths" to label the arguments of those opposing their views. Much of the debate in the media has lost any connection with the science at question. Arguments often focus around who said what rather than scientific facts. Despite almost unequivocal scientific evidence to support their case, many advocates continue to make the argument that 97% of climate scientists believe in anthropogenic global warming. This is not scientific evidence. Further, it is a misrepresented statistic. Findings of the paper being quoted with this statistic (Cook et al., 2013) are that only 32.6% of all articles on climate change expressed an opinion on anthropogenic warming in the abstract. Of these, 97% supported the theory. The remaining 67.4% of the articles analysed in this study did not articulate an opinion for or against anthropogenice warming in the abstract.

Both sides argue unethical conduct driven by conflicts of interest. Advocates accuse sceptics of being funded by the fossil fuel industry. Sceptics argue that there is a conspiracy; that scientists' claims of anthropogenic climate change are a bid to gain governmental control over energy consumption. Sceptics hacked email servers at a leading institution for climate research and posted (misrepresented) snippets of emails on the internet to support their conspiracy theory. Neither side of the debate is innocent.

The stakes of the debate and therefore the emotions of those debating are high. From the advocates point of view – the stakes are the wellbeing of the planet. They (like I) believe that failure to act is likely to mean severe consequences for humankind. However, to act, is unlikely to be a minor undertaking. Sceptics are reluctant to make changes of the order of magnitude believed necessary by advocates based on what they believe to be uncertain science.

It is understandable therefore that the debate is so fierce and sensitive. However, at the core, it is a debate over scientific evidence. This chapter does not explore who said what or the motivations of sceptics or advocates. It presents the scientific evidence for and against anthropogenic (human caused) climate change and attempts to address both sides of the argument with transparency. The chapter begins by introducing the concept of the Earth system. It then presents the core evidence for anthropogenic climate change. Those who do not believe in anthropogenic climate change generally fall into one of three categories: those who do not believe the climate is changing; those who believe the climate is changing but do not believe that this is caused by human activity; and those who believe human activity is changing the climate but do not agree that this is important. This chapter goes on to address the key arguments made against anthropogenic climate change under these three categories.

2.2 Earth as a System

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 (land), hydrosphere (water), atmosphere (air), and biosphere (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 and chemistry (Skinner, 2011). These processes have complicated relationships with many feedback loops. Feedback loops can lead to tipping points – points of abrupt and substantial changes to the state of the planet as described by global and local ecological references (Scheffer et al., 2001, Lenton et al., 2008). Climate change – a change in global average temperature – is an example of an Earth system process which has many feedback loops. For example:

> People emit carbon dioxide into the atmosphere. Carbon dioxide is a greenhouse gas – which means it traps heat into the atmosphere. The increased heat leads to a small decrease in the global surface area of ice, an area that is replaced by dark blue ocean. Ice is reflective. Dark blue ocean is not. The change in areas of ice and ocean lead to less total surface reflectivity (assuming other factors affecting Earth's albedo do not change). This means more heat is absorbed by Earth's surface. More heat means that more ice melts. Earth's reflectivity reduces further, and the feedback loop continues.

This is only one example. There are many other feedback loops that affect climate change and other Earth-system processes. Some, like the melting ice, are positively reinforcing, i.e., they accelerate change. Other feedback loops help to stabilise Earth-system processes. These are called negative feedback loops. The risk that we face today is that we may reach a tipping point – where the positive feedback loops accelerate change – resulting in rapid and possibly irreversible change, beyond our control. The state of the Earth system can change very rapidly. For example, the transition from the last glacial period, the Younger Dryas, to the current interglacial, is thought to have happened over only a few decades. In Greenland, temperature changes of as much as 10ºC per decade are believed to have occurred during this period (Severinghaus et al., 1998).

The Earth system can operate in many different states. Each state is typically separated by a relatively short period of rapid change. Average global temperature is not the only variable that changes from one environmental state to another. The chemical composition of the atmosphere, the amount of energy the Earth's surface receives from the Sun, the ratio of ocean to land area of Earth's surface, and the number and type of species inhabiting Earth are all examples of variables that can differ between different environmental states.

2.3 Human Activity is Changing the State of the Planet

The atmosphere currently contains more than 400 parts of carbon dioxide (CO_2) per million parts of atmosphere (ppm). This is higher than any level measured since we began measuring the amount of carbon dioxide in the atmosphere. There is *very high confidence*[1] that the amount of CO_2, and other greenhouse gases (GHGs) including methane, and nitrous oxide in the atmosphere is higher than it has been in 800,000 years (IPCC, 2013d). More importantly perhaps, is the rate of increase of these gases. CO_2 levels in the atmosphere are currently increasing at a rate between 100 – 200 times faster than the rate of increase that occurred at the end of the last ice age. There are other periods in history where CO_2 levels have increased rapidly – as we are increasing them today. These events have been highly destructive to life – causing mass global extinctions – i.e., more than 75% of the existing species on Earth went extinct in a short period of time.

It is not the CO_2 concentrations per se, that is concerning. Rather, concerns are for the anticipated impacts to the Earth system that this could cause. There has been a very strong correlation between CO_2 and global average temperatures over the last 800,000 years McInnes, 2014) (see Figure 3). It is *virtually certain* that globally, the troposphere has warmed since the mid-1900s (IPCC, 2013d). It is *extremely likely* that over half the warming that has been recorded for average surface temperatures from 1950 to now occurred because of human activity (IPCC, 2013d).

[1] The terms used to describe likelihood correspond to scientific probabilities as follows: "virtually certain" - >99% "extremely likely" >95%, "very likely" >90%, "likely" >66%, "more likely than not" >50%, and "very unlikely" <10%. The term "very high confidence" conveys a 9/10 chance of being correct.

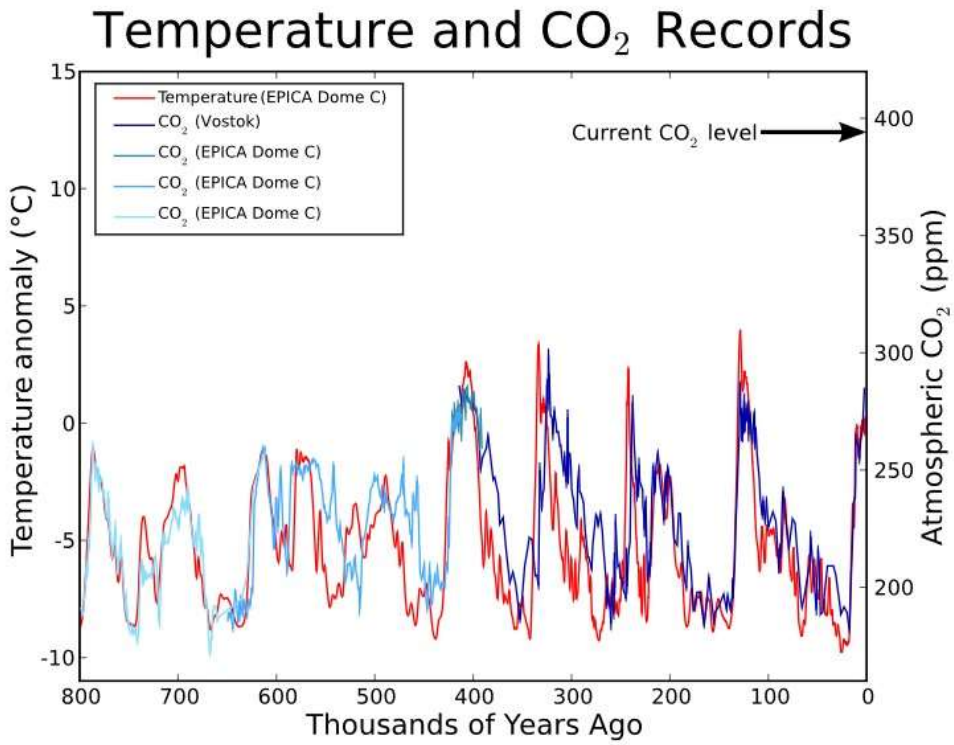

Figure 3: Average change in temperature with respect to average Holocene temperatures and atmospheric concentration of CO_2 ((McInnes, 2014) CC BY-SA 3.0[2])

It is not certain what increased average temperatures would mean for humanity, but predictions are not optimistic. It is *likely* that increased temperatures will lead to global average increase in rainfall, and that the rainfall distribution will change so that wet areas become wetter and dry areas become drier. It is *very likely* that the Atlantic Meridional Overturning Circulation (AMOC), the global flow of oceans that is an important component of Earth's climate system, will weaken; although it is *very unlikely* that it will collapse altogether this century. It is *very likely* that arctic sea ice will continue to shrink and thin and that global glacier volume will continue to decrease. It is *very likely* that sea levels will continue to rise and that the rate of sea level rise will increase. The likelihood of future increases to the frequency and/or intensity of extreme weather events ranges from *more likely than not* (for tropical cyclone activity) to *virtual certainty* (for warmer days and nights over most land areas) (Stocker et al., 2013, IPCC, 2013d).

2.3.1 Understanding CO2 and temperature

Figure 3 shows 800,000 years of CO_2 and temperature data, yet we have only been recording CO_2 levels since 1950. The estimates of past CO_2 levels in the atmosphere before 1950 are

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based on measurements of ancient air that is stored in glacial ice. The ancient air samples can also be used to estimate past temperatures because the composition of air changes with changing temperatures. Other independent evidence is then used to support ice core data. For example, the distance between tree rings indicates tree growth rate which is influenced by both temperature and CO_2 levels. There is tree ring data spanning 10,000 years which, until recently, showed a strong correlation with the ice-core data. Fossilised leaves can be used as another indication of past CO_2 levels. There is approximately 400,000 years of leaf fossil data and this correlates closely with ice core data. Lake and ocean sediments change with temperature, rainfall, and snowfall and can also be used to support ice core data (NOAA, 2018a).

Ice layers accumulate over hundreds of thousands of years which protects ancient ice from melting, thus storing important information about the past climate. However, heat from bedrock below the ice slowly melts the oldest ice so that until recently, ice core data had only been found dating back 800,000 years.[3] To determine CO_2 levels and temperatures before 800,000 years ago, proxy data such as isotopes found in shells and fossils of ancient marine organisms have been used. This data provides insight into the climatic conditions for the entire Phanerozoic period – i.e., the geological eon beginning 540 million years ago that we are still in today (Veizer et al., 1999, Berner, 1991, Berner and Kothavala, 2001, Crowley and Berner, 2001, Royer et al., 2004).

There have been several analyses of CO_2 and temperature data for the Phanerozoic period. Of these, most found a positive correlation between CO_2 and temperature: low CO_2 levels overlapped with extensive glaciations and high CO_2 levels did not (Berner, 1991, Berner and Kothavala, 2001, Crowley and Berner, 2001, Royer et al., 2004). One study did not find a positive correlation between the two (Veizer et al., 2000). However, it was found later that the temperature proxy data used in this study had not been corrected for seawater pH. Once the data had been updated the same positive correlation could be seen (Royer et al., 2004).

One of the arguments put forward by sceptics is that the phanerozoic CO_2 and temperature data are not coupled. This is because one period of glaciation occurred during this period which does not appear to correlate with low CO_2 levels. This glaciation, known as the late Ordovician glaciation occurred approximately 440 million years ago. The data suggests that

[3] Recently ancient ice, approximately 2.7 million years old, has been discovered VOOSEN, V. 2017. Record-shattering 2.7-million-year-old ice core reveals start of the ice ages. *Science.* There is not yet enough ice to draw strong conclusions from the findings. However, scientists are hopefully that this discovery will lead to a greater understanding of ancient climatic conditions.

this period of glaciation coincides with very high levels of CO_2 somewhere between 2400-9000ppm (Berner and Kothavala, 2001).

The correlation found by the authors who examined the phanerozoic CO_2 and temperature data pertains to *extensive* periods of glaciation. This is because the data is too coarse to draw any conclusions about shorter periods of glaciation. Extensive periods of glaciation do correlate with low levels of CO_2. Most of the shorter periods also occur at times when CO_2 levels are seemingly low.

The CO_2 data available for this period is in intervals of approximately 10 million years (Royer et al., 2004). In contrast, the late Ordovician glaciation is thought to have lasted less than 1 million years (Royer et al., 2004). Only one datum exists close to the period of the glaciation (Royer, 2006). This proxy data point cannot be more accurately dated than a point in time between 450-443 million years ago. It is conceivable that the CO_2 levels dropped during the Ordovician glaciation. There is geochemical evidence to support this theory. Carbon cycle modelling for this period suggests that CO_2 levels may have dropped to 3000ppm during the glaciation (Kump et al., 1999).

Even at 3000ppm it may seem unlikely that a period of glaciation could occur. Current CO_2 levels are a little over 400ppm and glaciers and arctic sea ice are melting. However, CO_2 is only one driver of average temperature. There are other factors such as Earth's orbit, and the intensity of radiation from the sun, that must also be considered. The current CO_2-ice threshold – the level of CO_2 below which glaciation is possible – is estimated to be 500ppm. This means that if all other factors such as the Sun's radiation and Earth's orbit around the sun remain constant, when the CO_2 levels reach 500ppm there will be no more ice on Earth. During the Late Ordovician the solar constant was 4% less than it is now. Royer (2006) estimated that in that case the CO_2-ice threshold would be approximately 3000ppm. This means that glaciation could occur at any CO_2 concentration below 3000ppm. Their estimate is consistent with other estimates for the Late Ordovician period which range from 2240 – 3920ppm (Crowley and Berner, 2001, Crowley and Baum, 1995, Gibbs et al., 1997, Kump et al., 1999, Herrmann et al., 2004).

The high CO_2 levels shown during the late Ordovician period are surprising. However, they do not negate the positive correlation found between CO_2 and temperature.

2.3.1.1 Correlation or Causation

Correlation does not mean causation (see Box 2.1). However, there is scientific evidence that there is a causal relationship between CO_2 and temperature. CO_2 is a greenhouse gas (GHG).

This means that it traps infrared radiation from the sun in the atmosphere and warms the planet. Without GHGs, Earth would not be habitable. With too many GHGs, Earth would become too hot, and Earth would also not be habitable. One of the arguments by sceptics is that the correlation of CO_2 concentration and temperature doesn't necessarily indicate causation. Further, they argue that historically, CO_2 has followed temperature – i.e., that temperature increases have caused CO_2 levels to increase rather than vice versa.

The relationship between CO_2 and temperature is more complex than this argument suggests. One does not lead the other. There are many positive and negative feedback loops that relate the two variables. For example, at the end of the last ice age Earth's orbital cycle led to warming in the Arctic. This warming caused large amounts of ice to melt – reducing the salinity of local sea water. The fresh water influx altered the natural ocean cycles and led to warming of the Southern Hemisphere oceans. The warmer oceans could not hold as much CO_2 so large amounts of CO_2 were released into the atmosphere. The increase in CO_2 in the atmosphere trapped more solar radiation and therefore increased the temperatures leading to more melting of ice and release of CO_2. In this example temperature increase was the initial driver that set the changes in motion. However, after this initial change, CO_2 then drove temperature increase (Shakun et al., 2012).

In summary, it is *extremely likely* that the CO_2 released by humans has caused and will continue to cause the global average temperature to increase (IPCC, 2013e).

Box 2.1: Spurious Correlations

There is a website dedicated to finding correlations in data sets which are clearly unrelated. For example, they show a 95.86% correlation between the per capita consumption of mozzarella cheese and civil engineering doctorates awarded from 2000 to 2009 (Vigen, 2018).

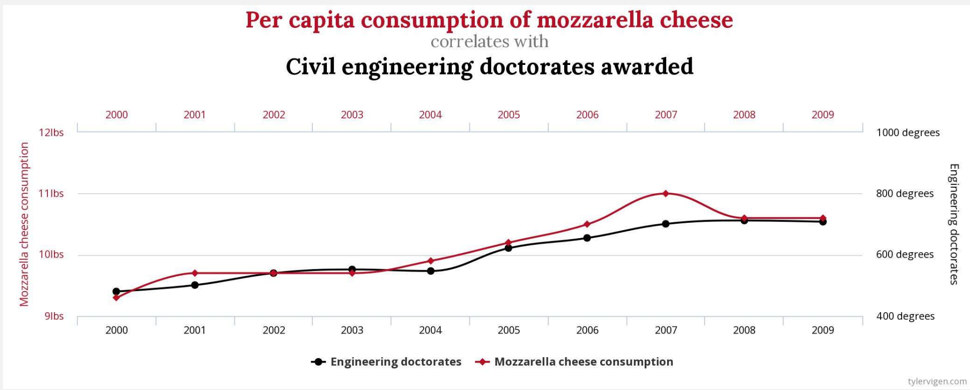

Figure 4: Data correlation between cheese consumption and doctorates awarded highlights that correlation does not mean causation ((Vigen, 2018) (CC BY 4.0))

2.4 Is the Earth getting warmer?

The global average temperature has not risen to the same extent as CO_2 levels since the industrial revolution. However, there is a definite warming trend since the beginning of the upward trend in CO_2 levels (see Figure 5). Data from many different sources shows that temperatures have risen by approximately 1.1°C since the industrial revolution (WMO, 2017a, Met Office, 2018, NOAA, 2017, Climate Copernicus, 2017, NASA, 2017).

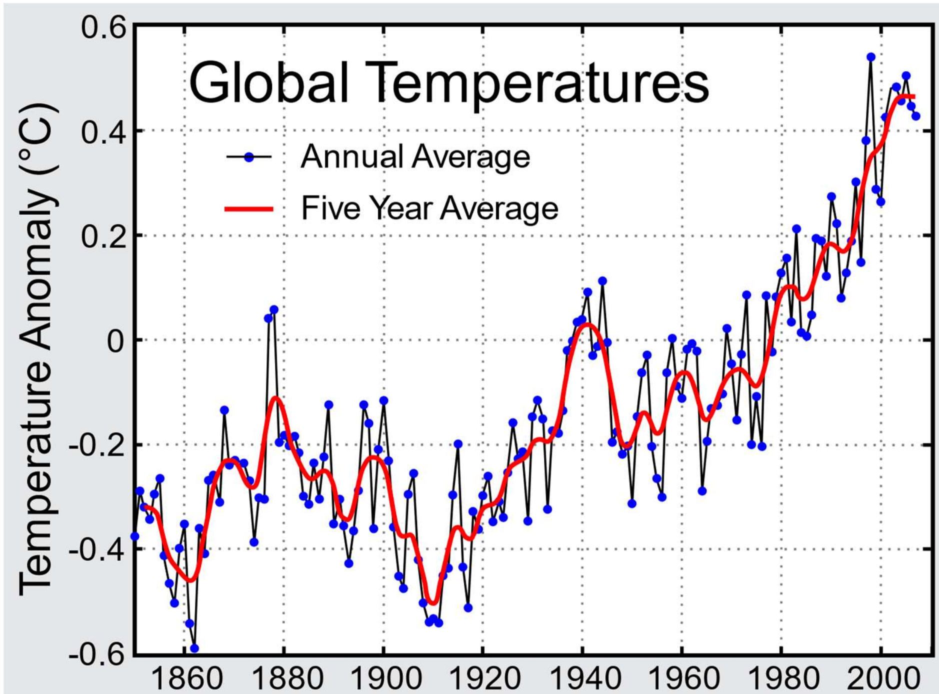

Figure 5: Global average temperatures since the industrial revolution showing a clear upward trend ((McInnes, 2008)(CC BY SA 3.0[4]))

In addition to the temperature data, there are many other lines of evidence that support the theory that the planet is warming. Greenland and Arctic ice sheets are getting smaller (Kjeldsen et al., 2015). Glaciers are melting (Kjeldsen et al., 2015). Sea levels have risen between 3-9 inches (Cole, 2017).

There are five key arguments frequently made as evidence that the planet is not warming:

1. In the 1970s scientists predicted that we were heading for an ice age.
2. 1934 was the warmest year on record.
3. There has been no warming since 1998.
4. The warming recorded reflects only the urban heat island effect.
5. Antarctic sea ice is increasing.

These theories are discussed below.

2.4.1 1970s predictions of an imminent ice age

One of the most widely touted arguments against the theory that Earth's climate is warming is that in the 1970s climate scientists were predicting cooling. From 1940 to the early 1970s there was a cooling trend (see Figure 6). In the early 70s, there was a period when the cooling

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trend appeared to be accelerating. In 1971 and again in 1972 there was an abrupt increase in the snow coverage area in the northern hemisphere of 12%. Areas that were usually void of snow in summer stayed covered all year round, and this continued in subsequent years. There were extreme droughts in Africa. Growing periods in England decreased by two weeks from 1950 - 1970, resulting in losses in the order of 100,000 tons of grain per year. Climatologist Kenneth Hare predicted that if 1972 conditions persisted for more than three years that the world's population would not be able to be sustained (LaHaye and Hindson, 1996).

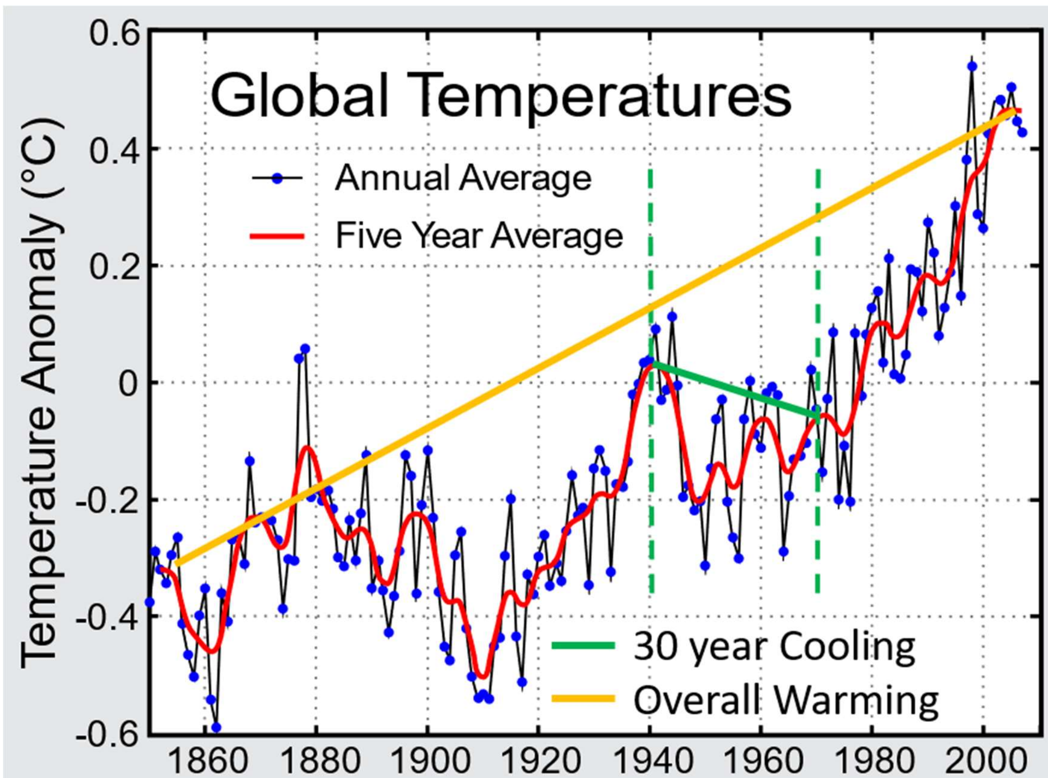

Figure 6: Cooling trend from the 1940s to 1970s within the overall warming trend since the industrial revolution (Adapted from (McInnes, 2008) (CC BY SA 3.0[5]))

During this period, several scientists did predict that the cooling trend would continue and warned of an imminent ice age:

- Rasool and Schneider (1971) predicted that the cooling effects of aerosols would outweigh the warming effects of CO_2;
- Bryson (1974) also concluded that aerosols cooling effects would exceed the effects of CO_2; and

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- Barrett and Gast (1971) suggested that warming was unlikely on the basis of his predictions that CO_2 doubling in the atmosphere would take 340 years.

All of these papers predicting global cooling made two important assumptions:

1. Human emissions of carbon dioxide will have a warming effect; and
2. Human activity can influence global average temperatures.

The idea that CO_2 in the atmosphere could warm up the planet was introduced in 1896 by Svante Arrhenius (Arrhenius, 1896). In the 1930s Guy Callendar was cautioning that warming was underway. By the 1970s, the theory that CO_2 and other greenhouse gases had a warming effect was not in dispute. By this time however, it was understood that human activity, including the burning of fossil fuels (which were very dirty at the time) could also have a cooling effect through the production of aerosols[6]. Many scientists were working to understand the complex interactions between human induced cooling and warming, e.g., (Rasool and Schneider, 1971, Bryson, 1974, Kellogg and Schneider, 1974, Manabe and Wetherald, 1975, Mitchell, 1972).

In the 1970s, it was still believed that an interglacial period (a warm period between ice ages) could not last more than approximately 10,000 years (this theory has since been disproven). It is a little over 10,000 years since the end of the last ice age, so it is unsurprising that some scientists believed that a 30-year cooling trend was indicative of the end of the current interglacial period.

Despite the cooling trend, and the timing of the last ice age, many scientists in the 1970s were still predicting warming. Schneider, who in 1971 predicted cooling, co-authored another paper in which the authors acknowledged that the effects of aerosols were poorly understood. In this paper the authors estimated 0.5ºC of warming by 2000 (Kellogg and Schneider, 1974). Another author predicted 0.8ºC warming over the 20th century (Manabe and Wetherald, 1975). Another suggested that CO_2 would be more influential in its' warming effects than aerosols in their cooling effects (Mitchell, 1972).

The idea of an imminent ice age sparked much attention at the time. Hundreds of articles were published on the subject across a wide range of media. Some current day articles still cite these media articles as evidence of "alarmism" by scientists e.g., (Newman, 2017a). Some

[6] Aerosols are small particles suspended in the atmosphere which absorb and scatter light. See Chapter 12 for a more detailed description of aerosols and their effects.

sceptics draw from this previous, incorrect theory to conclude that there is no reason to believe scientists who are now warning of global warming.

There are certainly similarities in the nature and message of the articles from the 1970s and media articles on global warming today. A 1975 Newsweek article called "A Cooling World" begins:

"There are ominous signs that the earth's weather patterns have begun to change drastically…".

The article warns of pending food shortages and extreme weather conditions - a "grim reality". An earlier article from *Time* magazine published in 1974 called "Another Ice Age?" which predicts cooling of 2.7F (1.5°C) makes similarly ugly predictions:

"Whatever the cause of the cooling trend, its effects could be extremely serious if not catastrophic..."

A 1973 Science Digest article - Brace Yourself for Another Ice Age – warns:

"the end of the present interglacial period is due soon".

A more recent article published in the Washington Times in (1998) by Fred Singer, an atmospheric physicist at George Mason University, gained wide traction against the theory of global warming. His article refers to a report by the US National Academy of Sciences (NAS, 1975):

"…But this exaggerated concern about global warming contrasts sharply with an earlier NAS/NRC report … There, in 1975, the NAS "experts" exhibited the same hysterical fears – this time, however, asserting a "finite possibility that a serious worldwide cooling could befall the Earth within the next 100 years…"

It is understandable that these quotes, taken in isolation, might lead a person to feel that it was all unfounded hysteria in the 1970s and therefore conclude that the situation is similar now. However, the details of the articles cited above tell quite a different story to the quotes on their own. For example, A Cooling World goes on to say that the causes of ice ages remain "a mystery" and quotes a different section of the same NAS report cited by Singer which reads: *"Our knowledge of the mechanisms of climate change is at least as fragmentary as our data…. Not only are the basic scientific questions largely unanswered, but in many cases we do not know enough to ask the key questions".* Another Ice Age? qualifies the prediction for cooling as "*at best an estimate*". This article highlights that some scientists believe that the cooling trend is only temporary and, importantly, that "*all agree that more information is needed about the major influence on the earth's climate".* Brace Yourself for Another Ice Age clarifies that "soon" (the timeframe identified for the end of the current interglacial period) referred to geologically soon – i.e., anything from 200 – 2000 years and states that *"scientists seem to think that a little more carbon dioxide in the atmosphere could warm things up a good deal".* Climate Change: Chilling Possibilities states, *"the cooling trend observed since 1940 is real enough ... but not enough is known about the underlying causes to justify any sort of extrapolation,"* and *"by the turn of the century, enough carbon dioxide will have been put into the atmosphere to raise the temperature of earth half a degree [C]".*

Singer's (1998) article grossly misrepresents the NAS report (1975) which is neither hysterical nor certain in its findings. The forward reads:

"*...we do not have a good quantitative understanding of our climate machine and what determines its course. Without the fundamental understanding, it does not seem possible to predict climate...*".

The report is a call for a major research programme on the climate on the basis of a growing awareness of the reliance of humanity's economic and social stability on the climate and on the potential for human activities to influence it. Singer's quote that the experts in the report are asserting a "finite possibility that serious worldwide cooling could befall the Earth within the next 100 years" comes from this paragraph:

"…there seems little doubt that the present period of unusual warmth will eventually give way to a time of colder climate, but there is no consensus as to the magnitude or rapidity of the transition. The onset of this climatic decline could be several thousand years in the future, although there is a finite probability[7] *that a serious worldwide cooling could befall the earth within the next 100 years. The question remains unresolved. If the end of the interglacial is episodic in character, we are moving toward a rather sudden climatic change of unknown timing, although as each 100 years passes, we have perhaps a 5% greater chance of encountering its onset. If, on the other hand, these changes are more sinusoidal in character, then the climate should decline gradually over a period of thousands of years. These climatic projections, however, could be replaced by quite different future climatic scenarios due to man's inadvertent interference with the otherwise natural variation."*

[7] Note that Singer used the word "possibility" in his quote where actually the word was "probability" – thus altering the sentence from an acknowledgement that there *could* be imminent cooling to a suggestion that this was *likely*.

The full paragraph shows careful consideration of the possible future climatic conditions as understood, as well as a high transparency regarding the lack of knowledge at the time. It is not hysterical. Nor does it suggest any certainty regarding the theory of an imminent ice age.

In 1976, the weather returned to normal and the cooling trend was abruptly over. It is now thought that two main drivers led to the temporary cooling:

1. A surge in the emissions of aerosols after World War II from the burning of dirty fossil fuels (i.e., the aerosols released led to cooling); and
2. A cool phase in the Pacific Ocean Cycle (this cool phase has again masked warming over the past 2 decades – this is discussed later in this chapter).

The argument by sceptics that the 1940 – 1970s cooling trend and scientists' predictions of a possible ice age should not be taken as evidence against global warming because:

1. Warming trends have been observed over a long period – since 1750 (WMO, 2017a, Met Office, 2018, NOAA, 2017, Climate Copernicus, 2017, NASA, 2017) .
2. There is strong scientific evidence that emissions of CO_2 cause temperature increase – this was not debated in the 1970s concerns over global cooling. Nor is it debated today.
3. One of the theories thought to have caused the temporary cooling is the emission of atmospheric aerosols. Scientists still believe that aerosols have a cooling effect on the atmosphere. Moreover, many are concerned that as we reduce aerosol emissions to improve air quality, some of the masking effects of aerosols on global warming will diminish and warming will accelerate more rapidly.

2.4.2 1934 - the warmest year on record

Another point commonly presented as evidence against global warming is that 1934 was the warmest year on record. This is not true. 1934 was the warmest year in the United States (US). It was not the warmest year globally. However, the argument gained a lot of traction with sceptics because an error in the GISS data had previously shown 1998 to be the hottest year in the US. This error has been taken as evidence that recent warming may not be as high as the data suggests. It is also used as evidence that the temperature data cannot be trusted.

2012 is now the hottest recorded year in the US. The hottest year globally was 2016 (WMO, 2017a, Met Office, 2018, NOAA, 2017, Climate Copernicus, 2017, NASA, 2017). It is plausible that there may be more errors in the data that have not yet been discovered. However, the global temperature data is a compilation of many different data sources. It is unlikely that isolated errors such as this will affect the global trends to a noteworthy degree. When the mistake was found in the US data, this only had a 0.185°C/decade impact to the global data – i.e., the change to the global mean was less than 1/1000 of a degree.

2.4.3 The 1998 – 2015 warming hiatus

In 2014 American politician Ted Cruz stated in a CNN interview that:

"The last 15 years, there has been no recorded warming. Contrary to all the theories that they are expounding, there should have been warming over the last 15 years. It hasn't happened."

This statement was based on atmospheric temperature data, which at the time, did show a hiatus in warming from 1998 until 2005. Data pertaining to natural systems is almost always noisy and non-linear with unexpected outliers and anomalies. Past and future global warming is about long-term warming trends. This does not mean that every year should be warmer than the last. Nor does it mean there will not be short periods of constant or reducing temperatures. There was a ≈30-year cooling period from the 1940s to 1970s within the last ≈250 years of warming (see Section 2.4.1). A 15-year hiatus in warming would not necessarily constitute evidence against the theory that the long-term trend is warming.

<u>Box 2.2: Understanding Temperature Data</u>

Average temperature data for the past 150 years is predominantly taken from a compilation of measurements made at sea. Sailors and ship captains have always been interested in sea and air temperatures and many logged extensive measurements.

The sailors did not anticipate that this data would be used in future to understand global conditions. As such, there were no consistent methods to test the temperatures. Methods also changed over time. In the early days, methods were coarse – sailors would drop a bucket overboard and measure the temperature in the bucket. Later, water temperatures were measured automatically when water was pumped into the engine room. The different methods result in slight variations in the measured temperature and actual temperature.

Scientists therefore use various mechanisms to interpret the data to attempt to account for the potential variations between measuring methods.

The perceived pause did puzzle scientists for many years however. Many developed theories to explain it, but none were conclusive. During this time, many sceptics took the combination of the pause, and lack of robust explanation to be strong evidence that the climate was not changing. In 2015, scientists at NOAA realised that the data interpretation methods they had used for ocean data was overestimating early temperatures and underestimating more recent temperatures (see Box 2.2). When they updated the method of interpretation to account for these inconsistencies, the data no longer showed a pause in warming.

Sceptics used this revision of data as evidence of a conspiracy theory. However, an independent study reviewed raw data from buoys, against satellite and sensor data to assess the NOAA findings (Hausfather et al., 2017). Their results matched the amended NOAA results.

2.4.4 Global warming or the urban heat island effect

Some argue that the warming trends shown in the data are not showing average global temperature increases but rather localised increases in urban temperatures caused by the Urban Heat Island effect (UHI) (see Box 2.3). Most temperature sensors are located in urban areas. The premise is that the urban locations of temperature sensors results in falsely high measurements. One paper suggests that as much as half of the global warming trend recorded from 1980 to 2002 can be attributed to the UHI effect (McKitrick and Michaels, 2007).

The concerns that the UHI effect could skew climate data are shared by climate change advocates. NASA and GISS go to considerable efforts to account for potential impacts of the UHI effect in their data. To do this, they compare long term trends of cities to long term trends in nearby rural areas and then adjust the urban trends accordingly so that the data is not skewed. The impacts of the UHI effect on the data prior to these adjustments have thus far been found to be minor.

Box 2.3: The Urban Heat Island Effect

Urban areas have dark, heat absorbing surfaces. They have less evapotranspiration (release of water to the atmosphere by plants) than non-urban areas. They often have poor air flow due to high rise buildings. These factors contribute a localised temperature increase known as the urban heat island effect. Urban areas can be as much as 2ºC hotter than the surrounds. Even within cities there is much local variation between temperatures recorded over roads and temperatures recorded over vegetation and light-coloured infrastructure.

2.4.5 Antarctic sea ice is increasing

Southern sea ice is increasing. How can this be true? This paradox is often used as evidence against climate change. However, this argument is not compelling. There is data that shows that atmospheric temperatures are increasing. There are also data that show that the oceans, including the Southern Ocean, are warming. In fact, the Southern Ocean, surrounding the Antarctic sea ice, is getting warmer by approximately 0.17°C per decade. This is faster than the global ocean warming trends of 0.1°C.

Localised increases in ice in the face of global average temperature increases in the oceans, atmosphere, and Earth's surface, does not constitute evidence that the global climate is not warming. The Earth system is complex with global and local climates and climate phenomena. Nonetheless, there are theories to explain that increasing sea ice may be caused by global warming (see Box 2.4).

> Box 2.4: Theories on why Antarctic sea ice is increasing
>
> There are two main reasons believed to be causing the increase in sea ice. The first is the effects of the ozone hole. Lower stratospheric ozone in this region has strengthened cyclonic winds that move sea ice around creating polynyas – areas of open water. An increased number of polynyas means more sea ice. (Gillett and Thompson, 2003)
>
> The second reason is increased precipitation caused by the warmer atmosphere. Increased snowfall onto land increases sea ice. Increased snow and rain falling on the surrounding water reduce the salinity of the water. Normally the ocean currents bring deep warm water to the region, which rises and melts sea ice. Reduced salinity in oceans increase stratification (the separation between shallow cold water and deep warmer water or vice versa). The increased stratification means that less warm water rises to the surface and therefore less of the sea ice is melted.

2.5 Humans activity is the main driver for the changes to the state of the Earth

Some sceptics accept that the climate is getting warmer but debate that human activity is causing this. Scientific investigation does not result in certain proof of a hypothesis. Rather, a hypothesis is proposed, and evidence is gathered to either support or dispel this. As such, it is not possible to prove without doubt that the human emissions of CO_2 (among other things) is causing global average temperatures to increase. However, we can examine the evidence to support this, and the evidence against it. We can also consider other hypotheses and the evidence around these to draw conclusions as to the most likely theory.

The evidence to support the hypothesis of human induced warming includes:

- CO_2 and other greenhouse gases have a warming effect;

- CO_2 concentration and temperature have been very closely linked for the last 800,000 years – the period during which we have a lot of data. The data spanning the last 540 million years also shows strong correlation between these variables;
- human emissions of CO_2 since the industrial revolution have increased substantially;
- the concentration of CO_2 in the atmosphere has increased since the industrial revolution at a rate that has not occurred in the last 800,000 years; and
- the amount of CO_2 released naturally into the environment is approximately equal to the amount of CO_2 absorbed by the environment (so one would expect that the release of additional CO_2 into the environment by humans would alter the balance).

The main hypothesis proposed as an alternative cause of global warming is that it is that it is caused by changes in the solar cycle. The evidence cited against anthropogenic warming is that human emissions of CO_2 are insignificant.

2.5.1.1 Is climate change caused by the Sun?

Total solar irradiance (the amount of energy coming from the sun) is higher now than it was in 1750. In the past, solar irradiance and global temperature were closely coupled, suggesting that the sun was the main driver of temperature change until recently. However, since the 1980s, temperature increases have accelerated while solar irradiance has been dropping (see Figure 7). This decoupling of solar irradiance and global temperatures is further evidence to support the hypothesis that human activity is the main cause of global warming.

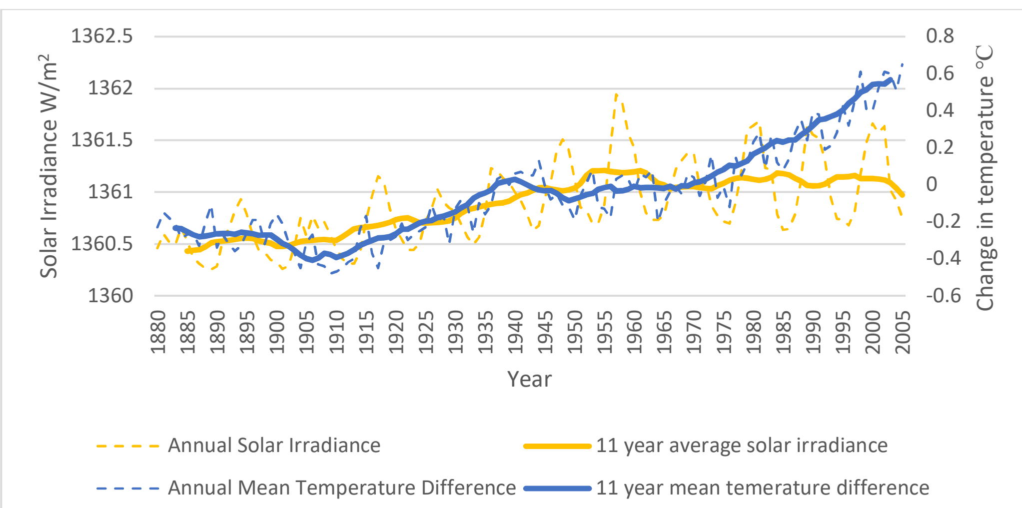

Figure 7: Average solar irradiance and average global temperatures have not correlated since the 1980s. Solar irradiance data from (Kopp, 2015), temperature data from (Schmidt, 2018)

2.5.1.2 Human emissions of CO_2 are insignificant

Without human intervention, approximately 750 billion tons of CO_2 are emitted naturally every year. Humans emit approximately 34 billion tons of CO_2 each year. Only a fraction of natural emissions. This means that human emissions constitute less than 4.5% of natural emissions. However, without human intervention, approximately 750 billion tons of CO_2 are absorbed naturally out of the atmosphere. The balance is the 34 billion tons of CO_2 emitted by humans.

The carbon cycle is self-regulating to a point. If the concentration of CO_2 in the atmosphere increases, the oceans, land, and vegetation absorb a little more carbon. This natural regulation has absorbed approximately half of anthropogenic CO_2 emissions (Ciais et al., 2013a). However, the other half, ≈17 $GtCO_2$ each year, remains in the atmosphere.

There are approximately 3,000 $GtCO_2$ in the atmosphere. This means that each year human activity is adding CO_2 in the order of magnitude of 0.5% of the total amount. However, since 1870, the end of the industrial revolution, humans have emitted approximately 2,000 $GtCO_2$. Approximately half of this has been absorbed into the carbon cycle[8]. This means that we have added approximately 1,000 $GtCO_2$ to the atmosphere, in approximately 150 years. This is an increase of 30%. At current rates, we will have increased the amount of CO_2 in the atmosphere by 50% by mid-century. In context, human emissions of CO_2 do not appear so insignificant.

[8] The amount of CO_2 that can is absorbed naturally is not fixed, but rather corresponds to the amount of CO_2 emitted. For example, emissions between 1980 – 1989 were much lower, at approximately 25 $GtCO_2$/yr. During this period the oceans and the land only absorbed approximately 13 $GtCO_2$/yr over the background rates. Once again, a little over half of the anthropogenic emissions were absorbed. It is not known whether the natural carbon cycle will continue to absorb half of anthropogenic emissions. Moreover, the absorption of additional CO_2 into the natural carbon cycle is not without consequence. For example, increased CO_2 absorption by the oceans is the cause of increasing ocean acidity which is a dangerous consequence for marine life.

Box 2.5: Altering a balanced system – the bath tub analogy for climate change

Consider a bath tub, that has just the right amount of water in it. If you pull out the plug, the water will begin to flow out. However, if you turn on a tap to the so that the amount of water running into the bath is equal to the amount of water escaping the bath, the water level will remain constant. This is (more or less) how the natural carbon cycle works. Now consider that every minute, someone adds a few drops of water to the bath, just 0.5% of the total amount of water in the bath (representing human emissions of CO_2 to the atmosphere). The effect of additional water is barely noticeable at first. However, in less than 2 hours, more than half of the original volume of water would have been added. Even if the bath was only half full to begin with, it would only be a matter of time, before it overflowed. The atmosphere will not overflow. However, the analogy helps to demonstrate the potential impacts of very small inputs to a balanced cycle.

2.6 Climate Change Matters

Some sceptics argue that there is no reason to be concerned about the changing climate because the climate has always changed. They make the point that life on Earth has flourished in periods of high CO_2 such as the Eocene and the Cretaceous periods. It is true that the climate has always changed. Figure 8 shows average temperatures over the past 500 million years. Temperatures have been as much as 14°C hotter and several degrees cooler than current temperatures.

During the past periods of high CO_2, at least those during which life flourished, the greenhouse gases were in balance. There are other periods in history where the CO_2 levels have increased rapidly – as we are increasing them today. These events have been destructive to life – and are thought to be the cause of some of the past global mass extinctions when almost all life on Earth went extinct.

Humans have only been around for approximately 300,000 years. During this time the climate has changed a lot. Humans have survived through several ice ages and an interglacial that is warmer than today (see Figure 8). However, for much of human history humans subsisted as hunter gatherers. It is only in the last 10,000 years, under the much more stable conditions that humans have developed into settled agricultural societies.

Even during the last 10,000 years there have been brief (several hundred year) periods of cooler and warmer temperatures including the late antique little ice age from 536-660AD, the little ice age 1300 – 1700 AD and the early medieval warm period from 950 – 1,200 (see Figure 9) . These periods of warmer and cooler temperatures were not as ubiquitous as recent warming (Stocker et al., 2013). Nonetheless, these periods are marked by great social upheaval. The end of the Late Antique Ice Age led to large scale migrations that contributed to the decline of the Western Roman Empire. The Mayan collapse can be linked to draughts caused by climate change. Even without global climate change, past societies have collapsed because of human impacts on the environment. This has happened even after warnings that collapse was imminent. Cities have been deserted after failure of their inhabitants to heed cautions of over consumption of natural resources. (Diamond, 2005)

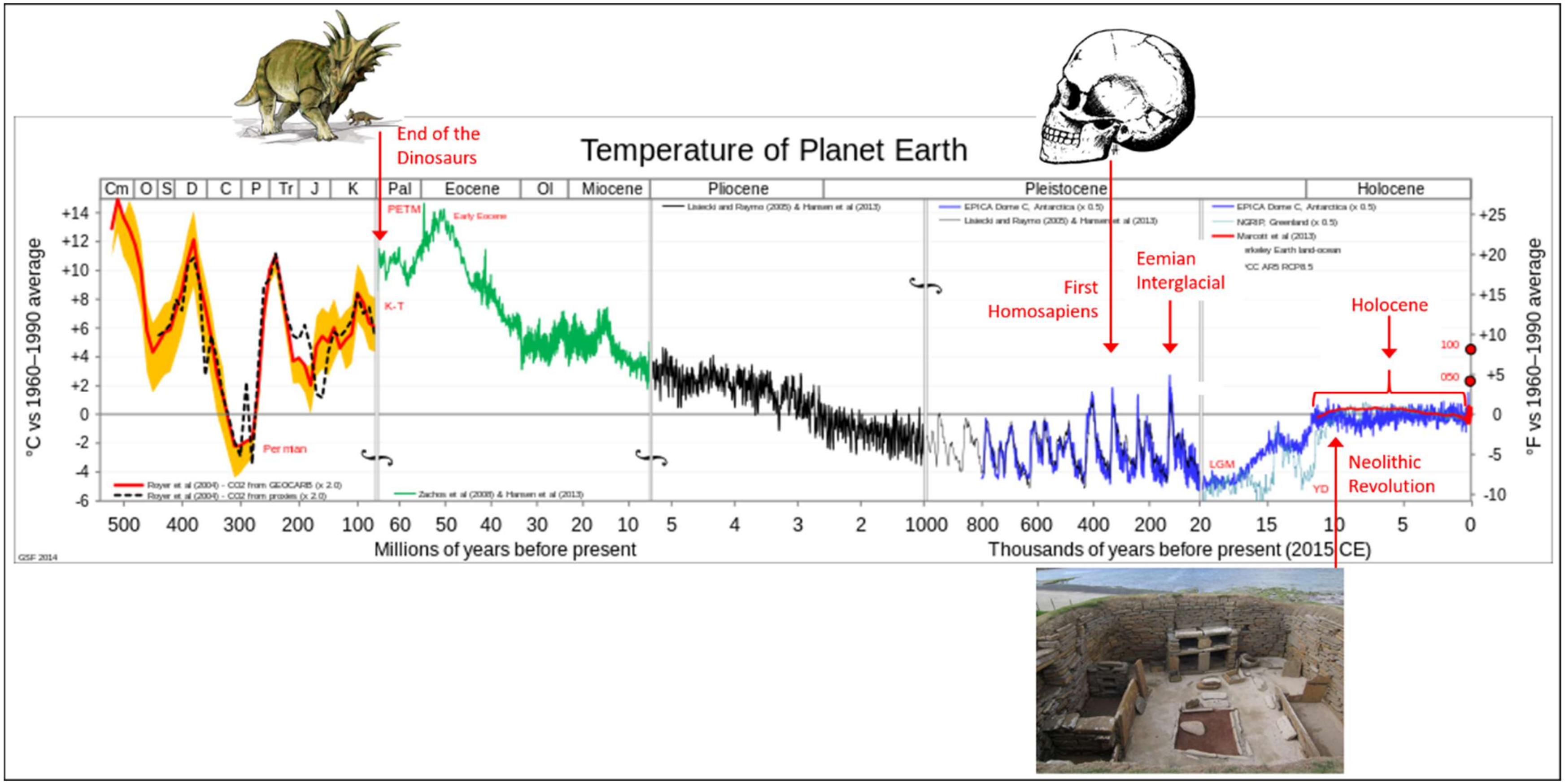

Figure 8: Average global temperatures on Earth during different geological epochs over the last 500 million years (Adapted from (Fergus, 2014, Benito, 2006, McKay, 2014) CC BY-SA 3.0[9])

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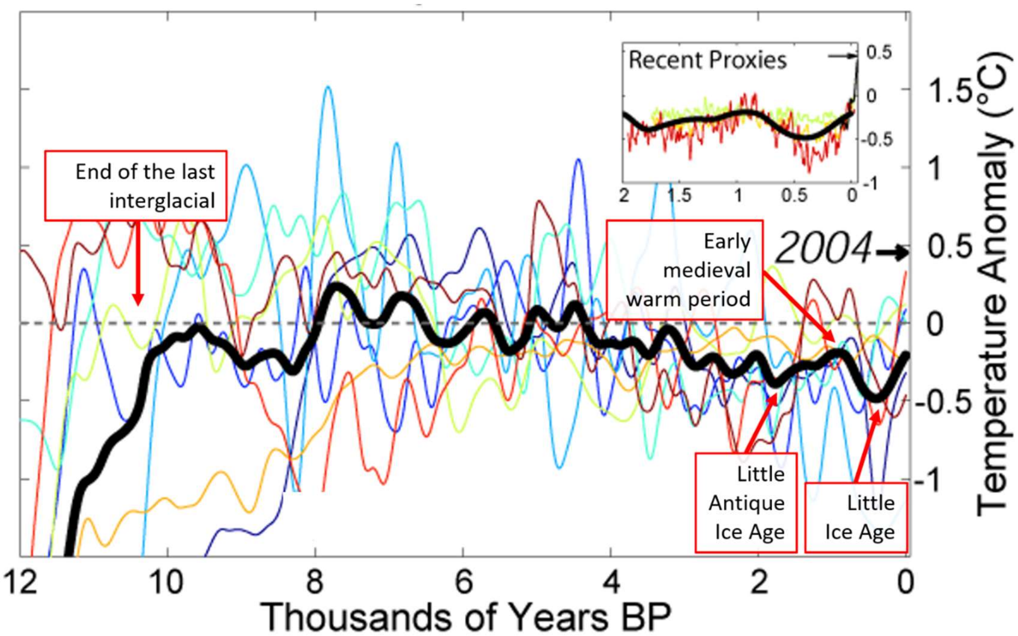

Figure 9: Temperature variations during the Holocene (adapted from (Rohde, 2010) (CC BY 3.0[10]) The coloured lines show proxy data, black line shows the average of these datasets. The dotted line shows mid 20th century average temperature.

The climate has always changed, but there have been negative consequences for life during times of rapid change. The difference now is that this is the first time that humans are causing the change. It is also the first time that humans have the capacity to prevent the change. Global limits may not yet have been exceeded to the point of no return, but evidence suggests that the point of no return may be close. Exceeding environmental limits is not a theoretical concern. It is a real one.

2.7 Conclusion

In summary, the scientific evidence shows with near certainty that climate change is happening, that it is predominantly caused by human activity, and that the potential implications are grim. Thus a major planetary limit does appear to have already been exceeded and suggests we must take seriously all the others as well as climate change. Climate change is only one Earth system process. There are many others, for example the nitrogen and water cycles, that are also being altered by human activity. It is important to understanding what level of impact from humans the Earth system can withstand before

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there are major changes to the Earth system function so that we can manage our activity accordingly.

The following chapter explores past and current attempts to define global environmental limits within which human activity should be managed.

CHAPTER 3

The Holocene, the Anthropocene, and the Planetary Boundaries

Abstract

People have been trying to determine environmental limits for the planet since as early as the 1600s. However, this task is inherently difficult as it requires a high level of value judgement. Assumptions regarding lifestyle, technology, population underpin most past attempts to determine planetary limits.

The Holocene is the period of time that started 11,650 years ago. This is only a small fraction of human history which can be traced back 300,000 years. Prior to the Holocene, the climate was highly variable. Humans lived as hunter gathers moving from place to place to survive. The Holocene was an unusually stable and warm period in human history. In this nurturing environment, humans developed from hunter gathers to urban and agricultural settled societies. The Holocene is the only state in which we know humanity can thrive.

We have now left the Holocene and are in the transition to the Anthropocene. This new geological epoch was named to acknowledge human influence on the state of the planet. The state of the planet in the Anthropocene is not yet determined, but at current trends in human activity, predictions are for a much hotter and less stable climate.

In 2009, the Planetary Boundaries were proposed. These are environmental limits for the planet below which the climate is likely to resemble the state of the climate during the Holocene. There are no assumptions regarding lifestyle, technology, or population underpinning the Planetary Boundaries. The limits are based on the latest scientific understanding of the planet's environmental processes. Four of the Planetary Boundaries have been exceeded.

It would be prudent for humans to try to return to and operate within the Planetary Boundaries so that the risk of changing the state of the planet from a Holocene-like state which is favourable to humanity is low.

3.1 Introduction

The task of defining the planet's environmental limits is not straightforward. There are no biophysical laws which define the limits. It is reasonable to assume that even with several degrees of global warming, Earth would continue to spin on its axis. When people refer to planetary limits, they are not usually referring to limits for the planet per se. Rather, what is normally meant by the term planetary limits is "limits for maximum planetary change that is acceptable for humanity". This means that there is a level of value judgement inherent in any definition of planetary limits. An acceptable level of planetary change is likely to be different for different people. For some, the only acceptable conditions might be those in which humanity is thriving. For others, it might be acceptable for humans to be simply surviving. Environmental limits for the planet would vary according to these different definitions of acceptable conditions (see Figure 10).

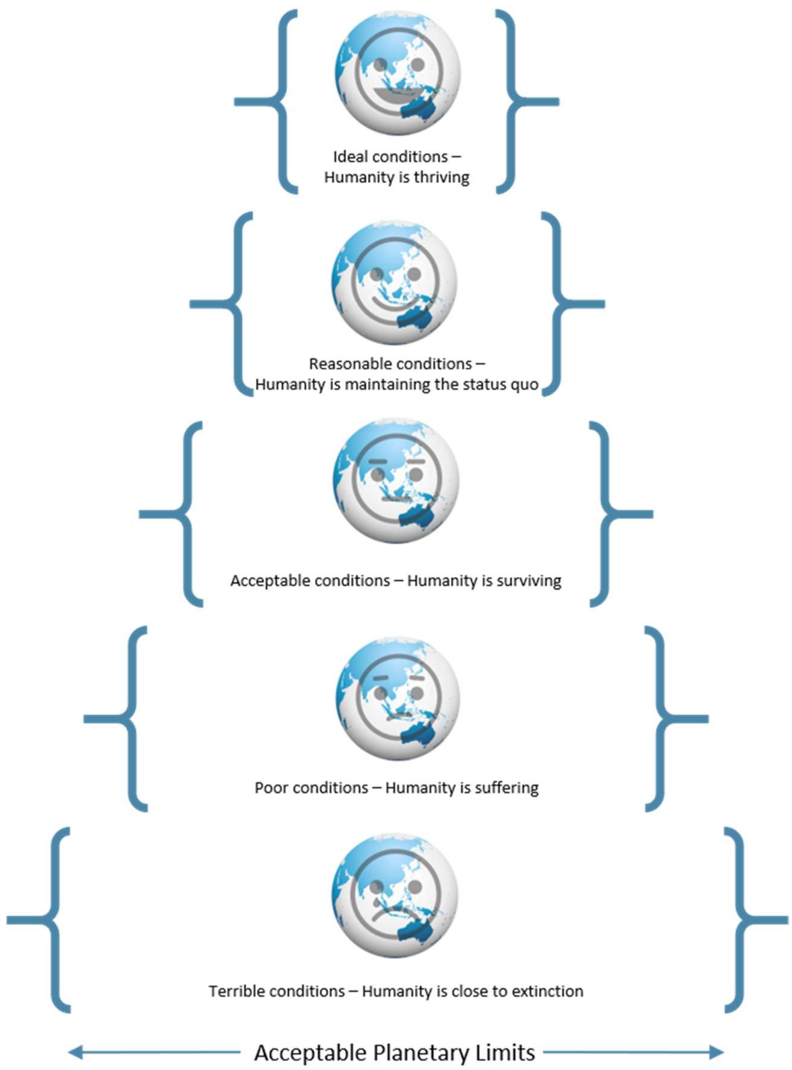

Figure 10: Planetary limits are dependant on the conditions deemed acceptable for humanity.

This chapter begins with an overview of how we have defined planetary limits in the past, and the limitations of these definitions. The Holocene and Anthropocene, the past and future states of the planet are then introduced to give context to the Planetary Boundaries. The chapter concludes with the case that humanity should aim to live within the Planetary Boundaries, and an explanation of what these are.

3.2 Planetary Limits – a brief history

The idea of planetary limits can be traced back to as early as the 1600s. Dutch scientist, Antonie van Leeuwenhoek, estimated Earth's "carrying capacity", the maximum human population Earth could support as 13.4 billion (F.N.L.P, 1962). His calculation was based on his estimate for the maximum population of Holland, multiplied by his estimate of the ratio of global inhabited land area to the area of Holland (F.N.L.P, 1962).

There have been at least 94 estimates of carrying capacity since Leeuwenhoek's (Cohen, 1995). Normally, with increasing numbers of studies of a scientific phenoMe-NOn, one would expect convergence of results over time. Interestingly, rather than trending towards a single value, the range in estimates of carrying capacity has increased over time (Cohen, 1995). Current estimates range from <1 billion to >1,000 billion with one outlying estimate at 1 sextillion (10^{20})(Cohen, 1995). Some of these estimates for the maximum number of humans Earth can support are substantially less than today's population. Some might argue that they must be incorrect on this basis. However, of the 7.5 billion people alive today, almost half live below the poverty line. This suggests that we are already living beyond the planet's capacity to equitably support all of us, in the long term.

To estimate how many people the Earth can support, one must first make some assumptions about what sort of lifestyle those people should have. These assumptions are the basis of the high variation in results. Estimates based on a high consumption lifestyle such as those experienced by many of the world's wealthiest today will be relatively low. In contrast, estimates which assume that only basic needs for food, water, and shelter must be met will be relatively high. The estimation of 1 sextillion includes cannibalism as a means to nourish the population (Franck et al., 2011).

The concept that human consumption could exceed the planet's capacity to provide to us became widespread when it was bought to light in Malthus' seminal Essay on the Principle of Population (1798). Malthus postulated that food supply would be unable to keep up with population growth because food supply had linear growth and the population was increasing exponentially. Later, as agriculture became mechanised and efficiencies improved, food production increased exponentially, and his theory seemed to be without foundation. However, in the late 1960s and early 1970s, as concerns mounted regarding limited oil supplies; other authors picked up the notion of the planet's limits (Ehrlich, 1971, Meadows et al., 1972, Tobin, 1971).

The book, *Limits to Growth* (Meadows et al., 1972) is the earliest recorded attempt at defining global scale limits. The authors do not specify global limits per se, rather, they discuss findings of a computer simulation of global future scenarios. The scenarios are modelled against five basic factors they deemed to be the key determinants in limiting growth:

population increase, agricultural production, non-renewable resource depletion, industrial output, and pollution.

Since the 1970s the idea of planetary limits, or more broadly, *sustainability* has become increasingly popular. The primary Oxford definition for the word *sustainable* is "able to be maintained at a certain rate or level"(Oxford Dictionaries, 2014). The use of this term to refer to operating within planetary limits seems to have developed gradually. The earliest use of the term in the context of planetary limits may have been by Meadows et al. (1972) when they wrote:

"*It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future".*

The idea of ecological sustainability is now so popular that the secondary Oxford definition for *sustainable* is "*conserving an ecological balance by avoiding depletion of natural resources*". The term sustainable development can be traced back to The Brundtland Commission (1987) which defines this as:

"*development that meets the needs of the present without compromising the ability of future generations to meet their own needs".*

The Brundtland definition of sustainability is still broadly used. However, since then, another common usage is *triple bottom line* sustainability. This concept was first documented by Spreckley (1987) and stems from the term "bottom line" as it is used in accounting – the total profit or loss – recorded at the end of a financial statement. The *triple* refers to environmental, social, and economic bottom lines.

Another approach to defining sustainability or planetary limits has been to develop a general set of rules for use in decision making, typically prohibiting:

- increasing concentrations of substances from Earth's crust in the atmosphere, hydrosphere, and biosphere,
- increasing concentrations of substances produced by society, and
- excessive physical manipulation or over-harvesting,

with a fourth rule pertaining to societal wellbeing (Robèrt et al., 2013, Broman et al., 2000, Goodland and Daly, 1996, Daly, 1990, Azar et al., 1996).

In 1989 Eugene Odum published a book entitled Ecology and our Endangered Life-Support Systems (Odum, 1989). It was an advanced book for it's time as it addressed ecology as an integrated system with a focus on the importance of the entire biosphere, down to the smallest of ecosystems. Odum refers to the failed engineering of Apollo 13, which exploded just moment's into its first flight. He postulates that if we cant even get a relatively simple life-support system that we designed and built right, we should be wary of tampering with the far more complex life-support system of our planet.

A decade later, Vitousek et al. (1997) wrote a paper outlining human's "domination" of Earth's ecosystems. Their paper identifies the key impacts of humanity on the Earth system which broadly encompass the same key Earth system processes that were later identified as having critical Planetary Boundaries (see Section 3.5).

Since the 1990s there have been many attempts at quantifying sustainable environmental limits. An overview of key environmental limits and their limitations are presented below:

Ecological Footprint/*Biocapacity* – the term Ecological Footprint, first mentioned in academic literature in 1992 (Rees), is perhaps the most famous system that includes some reference to environmental limits. It is a measure of human pressures (the Ecological Footprint) compared to the ability of Earth to provide (biocapacity). Both the footprint and the biocapacity are communicated in terms of weighted land area (Wackernagel, 1996). The Ecological Footprint was not intended to be a standalone indicator of sustainability (Ewing et al., 2010a). The intention was for it to capture all impacts which compete for space (Galli et al., 2014). The results of assessments can be communicated in terms of the number of planets that would be needed if everyone acted in the same way as the subject who had been assessed. For example, when I calculated my own impacts I had a footprint of approximately 2.2 "Earths". I.e., if everyone lived like me, we would need 2.2 planets to support this. The communication of limits in this way is highly effective. The problem lies in the implication of this message. If my footprint is 2.2 Earths, it seems reasonable to assume that any footprint less than one Earth is *sustainable*. This is not the case. A footprint of one Earth means that if everyone lived at this level, there would be no biocapacity for any species other than humans (Global Footprint Network, 2012). There have been estimates of how much biocapicty should be reserved to support other species. These are discussed in Section 5.4.1.

Planetary Guard Rails (WBGU, 1995) – The concept of guardrails was first developed in response to human induced climate change. Guardrails are defined as "quantitatively definable damage thresholds whose transgression either today or in future would have such intolerable consequences that even large-scale benefits in other areas could not compensate these" (WBGU, 2011). Guardrails have been proposed for:

- Global Warming – mean global temperature rise < 2ºC from pre-industrial times (WBGU, 1995),
- soil degradation – rate of soil erosion < 1 tonnes/hectare/year (WBGU, 2005),
- protected, conservation areas > 20% of global area of terrestrial and river ecosystems (WBGU, 2001),
- ocean acidification – pH decline compared to preindustrial pH < 0.2 units (WBGU, 2006),
- long lived and harmful anthropogenic substances (WBGU, 2014), and
- the loss of phosphorous (WBGU, 2014).

There is no clear consensus that the guard rails identified are sufficient in determining damage thresholds.

Tolerable Windows – This concept builds on the Planetary Guard Rail system – using these as an upper limit for human impacts. This system advances the Guard Rails, by including minimum societal needs that must also be met. The "tolerable window" is where societal needs are met within the environmental limits (the guard rails) (Petschel-Held et al., 1999).

Critical Natural Capital – This concept is based on the idea that environmental systems perform irreplaceable functions (Ekins et al., 2003), for example, bees pollinating plants. Critical natural capital is the level of environmental functions that are critical for humanity.

Many of these systems provide insightful contributions to the discussion of planet limits. However, none clearly define maximum acceptable planetary change for humanity.

3.2.1 The Population – Technology – Lifestyle Nexus

Ehrlich's popular book The Population Bomb (1971) began a long debate between environmentalists and economists regarding the importance of impacts of population growth on the environment versus the economy. There are also debates between environmentalists regarding the ethics of population control, and the role of technology versus behaviour in solving our environmental crises.

Ehrlich and Holdren (1971) proposed a simplified mathematical equation to define the relationship between human impacts on the environment and population, affluence, and technology:

$$I = PAT$$

I ~ environmental impact which can be expressed in any unit of impact.

P ~ population measured in persons

A ~ affluence measured in Gross Domestic Product (GDP) per person

T ~ technology in impact per unit of GDP

The premise of this equation is that an increase in population or affluence will have a proportional increase in impact. Likewise, any improvement in technology (a reduction in impact per GDP) will lead to a proportional decrease in impact. This is perhaps a useful tool in some instances. However, it makes incorrect assumptions about the simplicity of these three variables with respect to their impacts (Alcott, 2010). Take for example, an increase in a city's population by 100%. Using the IPAT equation we would estimate that the impacts of this city should double if technology does not change. However, the formula ignores the interconnectivity of the variables. An increase in population may lead to changes in both affluence and technology, for example, more efficient public transportation, factors which would not have been considered by the IPAT equation.

Notwithstanding the above, the IPAT equation can be used to understand the underlying problem inherent in many of the attempts to quantify planetary limits: There is a need for value judgement and assumptions regarding either population, affluence (or lifestyle) and technology in many of the past attempts to define environmental limits. The example above of the estimate for carrying capacity, where cannibalism is assumed to be reasonable sustenance, is an extreme example. On the other hand, Malthus's predictions that food supply would not match population growth (1798) probably seemed quite reasonable to most at the time. Yet, they did not come true because Malthus assumed future food production would follow past trends. He did not predict the advancements in food production technology.

Even definitions of limits that do include assumptions regarding technology or lifestyle have a level of value judgement as to the level of planetary change humans are willing to accept. The fundamental problem is that there are no biophysical laws which can be used to determine the limits (Van Vuuren et al., 2016).

3.3 The Holocene epoch

The Holocene is the period of time which began 11,650 years before present (taken as the year 2000) (Severinghaus et al., 1998). Since the start of the Holocene, the state of the Earth system has been unusually stable, with average global temperature ranges of only ±1ºC. Homo-sapiens evolved approximately 300,000 years ago, during the previous, Pleistocene epoch (Ewen, 2017). The Pleistocene was a less stable epoch than the Holocene, marked by abrupt temperature changes as can be seen in Figure 8. It is evident that homo-sapiens can survive in different Earth-system states. Humankind survived through two ice ages and a brief interglacial period much warmer than current average temperatures (Jouzel and Masson-Delmotte, 2007). However, during this period, for more than 280,000 years, humans subsisted as hunter gatherers, moving from place to place so that they could survive.

The Holocene is both warmer, and more stable than any other 10,000 year period of human history (IPCC, 2007) (see Figure 8). At the beginning of the Holocene, almost simultaneously, agriculture began in seven to eight geographically separate regions across the world (Bocquet-Appel, 2011). This period is known as the Neolithic Revolution (Bocquet-Appel, 2011).

Historians do not suggest that the change in climate was a driver for the civilisation of humanity. They believe that humankind already had the intelligence and knowledge needed to begin the transition and the Holocene presented the needed “window of opportunity” for this to happen (Cook, 2005). The warm and stable temperatures in the Holocene epoch enabled the rapid development of humans from hunter gatherers to urban, agricultural, and industrial settled societies (Rockström et al., 2009e, Bocquet-Appel, 2011).

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 (Rockström et al., 2009e). Yet many scientists believe that the Holocene is over. They believe that we are in the transition to a new epoch – the Anthropocene (Rockström et al., 2009e, Crutzen, 2002, Zalasiewicz et al., 2011). It is unknown whether society can thrive in other environmental states. It is also unknown what state the Anthropocene will have.

3.4 The Anthropocene epoch

The Encyclopaedia of Global Environmental Change (Trenberth, 2002) lists key external forces which can alter the Earth system as:

- the Sun and it’s output;
- the rate of Earth’s rotation;

- Sun-Earth geometry and the changing orbit of Earth around the Sun; and
- Earth's physical makeup:
    - distribution of land and ocean;
    - geographic features on land;
    - ocean bottom topography and basin configurations; and
    - mass and basic composition of the atmosphere and ocean.

Many scientists now believe that human activity should be added to this list as we have become a primary driver of the Earth system (Steffen, 2005, Zalasiewicz et al., 2011, Rockström et al., 2009e). The new Anthropocene epoch is named as such to acknowledge the role humans are now thought to play in determining the state of the Earth system (Paul, 2002, Crutzen, 2002, Zalasiewicz et al., 2011).

Epochs are delineated through geochronology – rock dating. By definition, the beginning of any new epoch must be marked by a globally dispersed signal found in rock layers and deposits (Zalasiewicz et al., 2011). There is substantial evidence of such rock deposits which could be used to justify the start of the Anthropocene. Signals human activity has left in the rocks include radionuclides from nuclear testing, unburned carbon spheres from power stations, plastic pollution, aluminium and concrete particles, and residue from fertilisers (Lewis and Maslin, 2015). It is interesting to note that many of these signals do not relate to climate change. This suggests further evidence of the multitude of global environmental impacts humans are having on the planet.

There are external factors which could change the state of the planet that are beyond human control, for example, the output of the Sun, or the shape of Earth's orbit around the Sun (Trenberth, 2002). In the 1970s, scientists believed that the Holocene was nearing its' natural end and that without human intervention the Earth system would be headed into another ice age (Kukla et al., 1972). However, more recent evidence suggests that without human interference the Holocene would be expected to continue for another several thousand or even tens of thousands of years (Berger and Loutre, 2002). This estimation is based on our understanding of the solar cycle (the changing output of the Sun), and patterns of change to Earth's orbit.

Of course, it is possible that the Holocene would come to a natural end sooner without human interference. There could be natural drivers we cannot predict, for example a meteor that alters the orbit or the composition of the atmosphere, or a major tectonic event (shifting plates under Earth's crust). However, such events are beyond our control. What we can influence are human impacts on the state of the Earth system.

Scientists are debating the precise start date of the Anthropocene. However, the dates proposed all fall within a timeframe of 1-2 centuries. This is an extremely short window in geological timeframes. Whatever date is finally agreed upon, we are currently operating at the intersection of the Holocene and the Anthropocene. The state of the planet is no longer truly a Holocene-like state (see Figure 11). However, the long-term state of the Earth system in the Anthropocene is yet to be determined. The Anthropocene could mean a human-managed Holocene-like state, or an entirely new, warmer, unknown but likely unfavourable future (Rockström, 2010). A warmer Anthropocene is unlikely to occur through gradual, linear change (IPCC, 2013d). Predictions are for dramatic and potentially irreversible change: substantial loss of species, devastating storms, significant sea level rise, and considerable displacement of communities (IPCC, 2013c). It seems prudent thus, that humans should aim for the Anthropocene to resemble the Holocene.

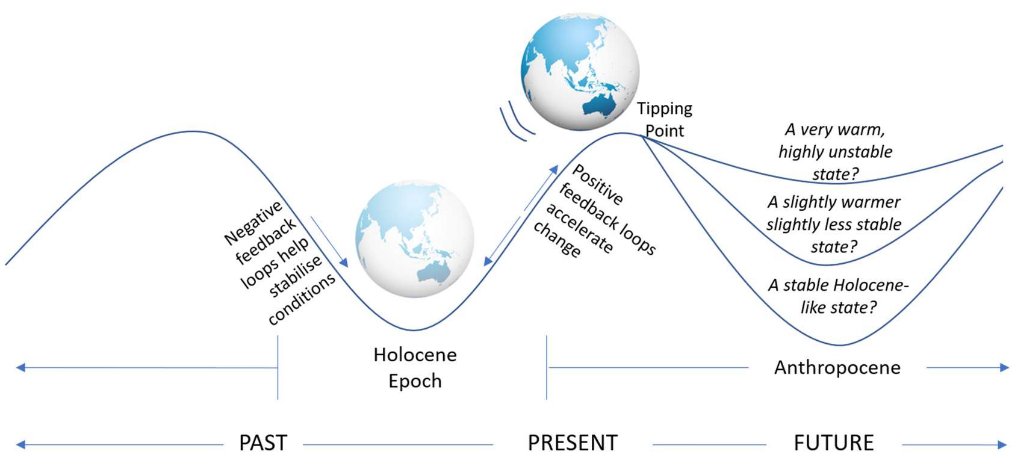

Figure 11: We have left the safety of the Holocene epoch, but the state of the Anthropocene is still to be determined

3.5 Planetary Limits for a Holocene-like State: The Planetary Boundaries

In 2009 (Rockström et al., 2009a) proposed a new set of planetary limits known as the Planetary Boundaries (PBs) (Rockström et al., 2009c). This was updated in 2015 (Steffen et al., 2015). The Planetary Boundaries are global limits for Earth-system processes below which the risk of departing from a Holocene-like state is low.

The Planetary Boundaries approach represents a breakthrough in defining planetary limits because the underlying assumption is that we ought to try to maintain a Holocene-like state.

Further, the Planetary Boundaries are, for the most part, a measure of the state of the global environment. This differs to past attempts at defining limits which have attempted to measure human relationships with the Earth system. While there is value judgement in the determination of the point at which the limits should be, these key differences mean that there are no assumptions regarding lifestyle, technology, or population. The authors determined key Earth-system processes that, if altered too far by human activity, could lead to a change in Earth-system state away from the "safe" Holocene-like state (Rockström et al., 2009c). They assigned levels for each process based on the scientific literature. Where the science on particular limits was uncertain, the authors adopted the "precautionary principal" – i.e., in the absence of scientific consensus, the limits were set at the point at which the authors consider risk to be low based on the available scientific evidence. This decision framework in the development of the PBs gives a transparency and robustness that is not present in similar systems such as the Planetary Guard Rails.

The concept of the Planetary Boundaries has been widely taken up by the academic and policy community as the most robust planetary limits published thus far. A title-abstract-keyword search in Scopus of "Planetary Boundaries"[11] returned 188 papers since 2009. Rockström et al's original (2009a) paper has over 600 citations at the time of writing.

Not all reviews of the PBs are positive. The key criticisms are as follows:

- The limits proposed are based on a scientifically precautionary approach – a point of very low environmental risk. This approach may not seem fair to less developped nations who are balancing the need to manage environmental impacts with the need to provide citizens with basic needs (Galaz, 2014, Galaz et al., 2012a);
- Boundaries will change over time because of advances in scientific knowledge, and interactions between boundaries (Steffen et al., 2015);
- There is a need for value judgement in determining what constitutes "low risk" under the precautionary approach (Van Vuuren et al., 2016)
- Information will need to be gathered from different agencies to monitor the Boundaries. Some agencies may be reluctant to share this information (Galaz, 2014)
- The Earth-system processes selected have been questioned (Lewis, 2012, Mario, 2009) as has the existence of global limits for some of the processes (Bass, 2009, Molden, 2009).
- There is no mechanism through which to address social well-being (Biello, 2012)

[11] Excluding those pertaining to the "planetary boundary layer"

- There is no international organisation to coordinate the range of international, cross-sectorial, and multi-organisational initiatives (a poly-scalar approach) that would be needed for humanity to operate within the Planetary Boundaries (Galaz, 2014)

Despite these concerns the PBs concept has been widely adopted. Several authors have placed the PBs into the context of the broader definition of sustainability – considering social equity as well as environmental sustainability (Raworth, 2012, Steffen and Stafford Smith, 2013). There have been studies which aimed to improve the assessments of individual boundaries e.g. (Carpenter and Bennett, 2011, Gerten et al., 2013, Mace et al., 2014a), and proposals for alternative boundary processes (Running, 2012). Barnosky et al. (2012) discuss the nature of the thresholds, and (de Vries et al., 2013b, Van Vuuren et al., 2016) propose alternative approaches to manage the complex interactions between the boundaries. Although not specifically referred to in the Sustainable Development Goals (SDGs), the concept was included in many of the SDG proposals including (SDSN, 2013, Griggs, 2013, UNEP, 2013). The UN High-Panel Level on Sustainability final report recommends that the PBs should be linked with policy(UN, 2012). The European Environment Agency (EEA) have identified the PBs as an environmental priority and proposed a vision that we should aim to be living within them by 2050 (EEA, 2011). Several authors have identified the PBs as an opportunity to use science to inform policy, e.g., (Brito, 2012, European Commission, 2012, Symons and Karlsson, 2015) and to form targets for Earth system governance (Galaz et al., 2012a). In a survey of eight European countries, seven reported that they found the PBs useful and important (Pisano and Berger, 2013). One study suggested that since the PBs are a synthesis of decades of research from fields related to Earth system science, they could be viewed as an operationalisation of the biogeophysical component of sustainable development (Galaz et al., 2012a). Others have highlighted the opportunity for the PBs to reform environmental governance at multiple scales (Galaz et al., 2012c, Cole et al., 2014, Akenji et al., 2016, Häyhä et al., 2016). The PBs have even sparked interest with religious groups; the Dalai Lama held a meeting to discuss the connections between choices and environmental consequences including the PBs (Galaz et al., 2012b).

The Planetary Boundaries are summarised in Table 1. There are nine critical Earth system processes and one or more global and/or regional control variables and limit have been proposed for eight of these.

Table 1: Summary of the Planetary Boundaries (from Steffen et al. (Steffen et al., 2015), Table 1)

Earth system process	Control variable	Planetary Boundary	Current Value
Climate change	Atmospheric concentration of carbon dioxide Change in radiative forcing	≤ 350ppm ≤ $1W/m^2$	396.5ppm* $2.3W/m^2$
Biodiversity loss	Global extinction rate	≤ 10E/MSY	100-1000E/MSY
Nitrogen and phosphorus cycle	Reactive nitrogen removed from the atmosphere Phosphorous flowing into oceans	≤ 62Tg N/y ≤ 11Tg P/y	150Tg N/y 22Tg P/y
Stratospheric ozone depletion	Stratospheric concentration of ozone measured in Dobson Units (DU)	≤ 5% below pre-industrial levels (290 DU)	~200DU over Antarctica in Austral spring
Ocean acidification	Mean saturation state with respect to aragonite in the oceans	≥80% of the pre-industrial level	84% of the pre-industrial level
Fresh water use	Freshwater consumption	≤4000 km^3/y	~2600km^3/y
Change in land-use	Area of forested land as a percentage of original forest cover	≥ 75%	62%
Novel entities	NA	NA	NA
Atmospheric aerosol loading	Aerosol optical depth	Regional limit of ≤ 0.25	.3 AOD over South Asian region

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
- *This was the value in 2015 when the PBs were updated. The current value is 405.51ppm (NOAA, 2018b)

Some of the PBs, such as the those for biosphere integrity and climate change, pertain to Earth-system processes which do not behave in a linear way and are likely to have tipping points. At certain threshold levels, these non-linear processes tend to undergo abrupt and sometimes irreversible change (Rockström et al., 2009c). Other PBs, such as those for nitrogen are not associated with tipping points. These PBs have been included because they undermine Earth-system resilience or increase the risk of reaching thresholds for other processes (Rockström et al., 2009a). Together, the PBs have been dubbed the “safe operating space” for humanity (Rockström et al., 2009a).

In 2009 when the PBs were conceived, three of the nine PBs had already been exceeded: for climate change, biodiversity loss, and nitrogen release (Rockström et al., 2009a). In a recent update of the PBs it has been shown that we have now also surpassed the limit for change in land use (Steffen et al., 2015).

3.6 Conclusion

Humans are in control of the future state of the planet. The state of the planet during the Holocene is the only state that we know is conducive to modern, agriculturally settled humans. There is evidence that we are in the transition to the next geological epoch, the Anthropocene, the long-term state of which is yet to be determined. Human activity is likely to be the major determinant of the state of the Anthropocene.

To minimise risk to humanity, we should aim for state of the planet in the Anthropocene to resemble that of the Holocene. The Planetary Boundaries are environmental limits within which the chance of changing the state from that of the Holocene is low. It follows that humans should aim to operate within these Boundaries.

The next chapter goes on to explore theories on global environmental management to show how we might begin to operate within the Planetary Boundaries.

CHAPTER 4

Managing the Earth System – Why we Need a Poly-Scalar Approach

Abstract

Human activity is altering critical natural processes beyond global limits. The way we manage the global environment over the next few decades will be a major determinant for the state of the Earth for the next epoch – the "Anthropocene".

Current efforts at managing the environment often take a top-down approach, an idea based on out of date theories of environmental management. Efforts at lower scales are often piecemeal, with no cohesion or common direction more than a general goal of reducing environmental impacts.

Three areas of social science; observed human behaviour, commons management, and change theory, can be used to show that a poly-scalar approach is needed to manage the Earth system. Such an approach would mean an approach which is integrative across different scales, sectors, and timeframes, that is not controlled by a single body, but which could be implemented through governance, privatisation, or self-organised management, that is coordinated by a general system of rules which have different mechanisms at different centres of activity.

4.1 Introduction

Despite global consensus that we are changing the state of the planet, we are failing to mitigate our behaviour at a rate befitting the urgency of the problem. As outlined in Chapter 3, we have already exceeded four Planetary Boundaries – safe environmental limits for humanity (Steffen et al., 2015). There is an urgent need to manage global scale impacts on the environment from human activity.

The problem is how. The phenoMe-NOn of our poor ability to manage shared resources known as "the commons" is not new. The idea can be traced back as far as 350BC to Aristotle (1996, Politics, Book II, Chapter 3, p. 33). Lloyd predicted irresponsible use of shared property as early as 1833 (Lloyd, 1977). Now humanity is faced with the challenge of managing the global environment.

The purpose of this chapter is to introduce a new theory of how the Earth System could be managed. Observed human behaviour change shows that pro-environmental decisions rely on an overlap of community, government, and business driven parameters. Commons management theories suggest that the most effective approach to managing the environment would be one which can be applied to different decision-making frameworks and at different scales. Change theory highlights the importance of overlapping interests across different sectors of society, and across different time horizons.

This chapter introduces these theories and shows how they can be brought together to make a case for a poly-scalar approach to Earth-system management.

4.2 Theories of Behaviour Change

Managing human impacts on the environment means managing human behaviour, whether this is individual day to day behaviour, behaviour as a CEO, as an innovator, or as a government official.

Early theories of behaviour change were based on the idea that people behave rationally, that behaviour was predictable. For example, the theory of planned behaviour is that one's beliefs are linked to one's behaviour – that if someone has the intention to perform a behaviour that they will do so. The theory of social norms is that a person's behaviour is influenced by their perception of others' behaviour – that they will be more likely to perform a behaviour if they believe that this is what is expected of them. The theory of cognitive dissonance is that people aim to be consistent with their attitudes, beliefs, and actions.

A Theorist's Workshop was held in 1991 (Fishbein et al., 1991) to assess and compare some of the most widely accepted models of behaviour change at the time and draw commonalities from these. This culminated in the identification of eight key factors which influence behaviour:

1. The person has formed a strong positive intention or commitment to perform the behaviour.
2. There are no environmental constraints that make it difficult for the behaviour to occur.
3. The person has the skills necessary to perform the behaviour.
4. The person believes that the advantage (benefits, anticipated positive outcomes) outweigh the disadvantages (costs, anticipated negative outcomes) of performing a behaviour.
5. The person perceives more social (normative) pressure to perform the behaviour than not to perform the behaviour.
6. The person perceives that performance of behaviour is more consistent with his/her self-image than inconsistent, or that its performance does not violate personal standards that activate negative self-sanctions.
7. The person's emotional reaction to performing the behaviour is more positive than negative.
8. The person perceives that he or she has the capabilities to perform the behaviour under a number of different circumstances. That is, they have the perceived self-efficacy to execute the behaviour in question.

The first four factors were considered "necessary and sufficient" for generating behaviour change. The remaining four were thought to influence the strength and direction of the intention.

These early theories led to the belief that the most effective ways to change behaviour were through the provision of information and feedback about the behaviour, as well as by influencing social norms.

More recent studies have advanced these theories. Studies based on observed human behaviour have shown that behaviour is very difficult to predict. Decisions vary with lifestyle, position within a family or within society, attitudes, motivations, habits, knowledge, past behaviours, social norms, context, and technology (Eon et al., 2017, Eon et al., 2018). Practice theory, for example, suggests that the context, as well as motivations, knowledge, technology, and habits must be addressed (Eon et al., 2017). In a framework for encouraging pro-environment behaviour, Steg and Vlek (2009) identify the three key factors which influence environmental behaviour as motivation, context, and habit.

An important difference in our current understanding of behaviour is that context and technology are key players in decision making. This means that to begin to change behaviour one must look more broadly than individual and community values and norms, motivations, habits, and knowledge. The roles of technology (business) and context (infrastructure and regulations) must also be considered. For example, smart phone aps which give live updates regarding bus and train timetables have been shown to significantly increase the use of public transport (Newman and Kenworthy, 2015). The provision of segregated bins for recycling increases recycling rates.

Thus, an effective approach to achieving pro-environmental behaviour is likely to be one which can encompass community values and norms, business innovations and technology, and government regulations and infrastructure.

Box 4.1: Scare tactics and behaviour change

Many efforts targeted at increasing individual's motivations to reduce their impacts on the environment focus on scare tactics. Images of polar bears on ice-caps, predictions of devastating weather events, and warnings of impending doom are rife in the media. They have little impact. Most people feel stressed and overwhelmed by the news (Newman, 2005). Some react by taking the less emotionally challenging the view point of sceptics (see Chapter 2). A more effective method is to provide a hopeful outlook: "If we do x, we can achieve y" (Newman, 2005).

Further, by identifying any positive past behaviours, one can help a person to strengthen their own identity as someone who cares for the environment. This identity can help to drive more change to low impact behaviours (Steg, 2016).

4.3 Theories of Commons Management

The first formal theories about the management of the commons began to appear in academic literature in the 1950s and 1960s (Olson, 1965, Hardin, 1968, Gordon, 1954). These early theories resulted in an assumption that either privatisation or top-down governance was needed to manage the commons. This assumption is still widespread today. A prevalence in top-down governance exists despite advances in the knowledge of human behaviour and commons management which suggest that there are more effective ways to manage the global environment and to drive change, such as an approach that applies to different levels of activity.

Box 4.2: Is the Earth System really a "Commons"?

A *common pool resource* or *common goods* are defined as resources or goods of which:

1. the exclusion of some users is difficult and,
2. the use of the resource or good is subtractible – the use of the good or resource by one person reduces the capacity for others to use it.

For example - Hardin's open pasture with limited grazing is a commons. As the pasture is open, it therefore meets the exclusion criteria. The more cows that graze the pasture, the less grass per cow. The resource is thus subtractible.

The Earth System is not by definition a commons. It meets the first criteria. However, it does not always meet the second. A person breathing from the atmosphere does not reduce the capacity for others to do the same. Officially the Earth System is defined as a "public good". Environmental impacts, for example pollution, are referred to as "public bads".

It is generally agreed by experts in the field that the behavioural dynamics around public goods, public bads, and commons are similar and that common pool resource theory can thus be applied to all three. (Ostrom et al., 1961, Lo and Tang, 1994, Gardner et al., 2000)

4.3.1 Conventional Theories on Managing the Commons

The most famous of the conventional theories is Hardin's "tragedy of the commons" (1968). He writes:

"*Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons*" (p1244) (Hardin, 1968).

Hardin explains the theory of the commons using the example of an open pasture for cattle. Before the pasture reaches capacity, each cow grazed on the pasture can be sold for the value of 1. Once the pasture reaches capacity, an additional cow added to the pasture would result in a loss to the value of 1/x per cow, where x is the total number of cows. A farmer adding a cow beyond the pasture's capacity would thus receive almost the full gain from the additional cow, while the losses from over grazing would be distributed evenly across all the cows, and therefore shared by every farmer. Hardin argues that the rational decision for each farmer is thus to add more cows, until such point that the pasture can no longer support any cows at all. Herein lies the tragedy (1968).

One may argue that group logic should prevail in such an instance. That the farmers should realise the tragedy and coordinate their behaviour. The counter argument to this is that in any group attempting to act for the greater good, there risks the presence of “free riders”. Free riders are actors who reap the long term benefits of positive action by others without contributing to the upfront costs (Ostrom, 1990). The existence or even anticipation of free riders has been found to influence others’ behaviour towards individual gain rather than group wellbeing (Olson, 1965, Ostrom, 1990).

A variant of the tragedy of the commons was proposed by Olson, “Collective Action”(1965). Olson postulates:

"Unless there is coercion or some other special device to make individuals act in their common interest, rational self-interested individuals will not act to achieve their common or group interests” (Olson, 1965)(p2).

His theory was not specifically about commons, but rather group behaviour in general, and has led to further work on related topics such as voluntary compliance, and lobbying group activities (Rupasingha and Boadu, 1998).

Both theories are based more broadly on the “Prisoner’s Dilemma”. Two (guilty) prisoners are simultaneously questioned. There are four possible outcomes:

1. Both prisoners remain silent; both face 1 year in prison.
2. Both prisoners testify; both face 2 years in prison.
3. Prisoner A testifies against Prisoner B, while Prisoner B remains silent; Prisoner A is set free, Prisoner B faces 3 years in prison.
4. Prisoner B testifies against Prisoner A, while Prisoner A remains silent; Prisoner B is set free, Prisoner A faces 3 years in prison.

The game does not allow for any communication between prisoners and assumes there is no risk of future consequences of ousting the other prisoner. Thus, according to the rules of the game, both prisoners will testify, even though this leads to the worst possible outcome (i.e., a total of four prisoner years).

It is easy to see how this theory could be applied to our response to so many of our environmental dilemmas. Take the release of greenhouse gases into the atmosphere as an example. We know that greenhouse gas levels are well above safe limits and that if we are to avoid severe temperature increases, we must stop emitting them. Yet, if you consider an individual deciding whether to drive or take the train on a rainy day, one can understand how the potential environmental benefits of this one train ride might seem easily dwarfed by the scale of the problem. Moreover, if the individual looks out the window and sees many “free riders” staying dry in the comfort of their cars, they may feel even less motivated to make the effort for this small payoff.

Those who subscribe to the theory of the commons typically propose either the privatisation or the top-down governance of shared resources (Ostrom, 1990). There are some very successful examples of both management structures. For example, the Montreal Protocol is considered by most to be a highly successful example of global top-down governance (Epstein et al., 2014), although it could be argued that it is not an example of top-down governance at all (see Section 4.5.1).

However, there are constraints and barriers in any management structure. In the example of the atmosphere – there have been several decades of attempted global, top-down governance to manage climate change. Yet, the development of a global solution has been problematic with many aspects that are hotly debated including the magnitude of emission reductions required, the methods and strategies to achieve emission reductions, and the division of responsibilities and costs. The recent Paris Agreement can be viewed as a substantial achievement in global policy (Schleussner et al., 2016). However, the nationally determined contributions under the agreement are estimated to correlate to warming of 2.7ºC-3ºC, well over the Paris target of 1.5ºC (Schleussner et al., 2016, Sharma, 2016).

4.3.2 Modern Theories on Managing the Commons

In the 1980s and 1990s there was a substantial body of theoretical literature that contradicted the arguments of the conventional theories, including by Hardin himself (Hardin, 1982, Marwell and Ames, 1980, Ostrom et al., 1994, Runge, 1981, Runge, 1984, Sandler, 1992, White and Runge, 1994).

Nobel Prize winner Eleanor Ostrom began a movement in 1990 which disputed the validity of the theory of the commons altogether. She showed through empirical evidence that the theory that individuals and small groups will not change their behaviour without external enforceable rules is far from inevitable. There are many studies showing examples of well managed shared resources such as forests and fisheries (Ostrom, 1990, Bernard and Young, 1997, Freeman, 1989, Korten, 1987, Korten and Klauss, 1984, McCay and Acheson, 1987, National Research Council, 1986, Ostrom, 1988, Siy, 1982). In some instances these self-organised regimes have proved more effective than would have been feasible in the case of privatisation or top-down governance (McKean, 1998, Ostrom, 2010) (see Box 4.3).

Studies of observed human behaviour show that the overarching factors which lead to cooperative behaviour by individuals towards the commons are:

- the development of trust that the behaviour will lead to long term benefits even if there are short term costs, and
- the belief that the majority of actors are performing this behaviour (Ostrom, 2009).

"Keeping up with the neighbours", a study rolled out by the Sacramento Municipal Utility District is a good example of how trust in others' actions can promote positive behaviour change. Personalised reports of power consumption with comparisons to their neighbours' consumption were given out to a portion of the residents. Those who received the personalised reports reduced power consumption by significantly more than those who did not (Kaufman, 2009).

Box 4.3: Alanya Fishery

Ostrom uses a fishery in Alanya, Turkey to demonstrate how self-governance can be more effective than privatisation or top-down governance.

The fishery of approximately 100 fishers was in a bad way from overharvesting and conflict amongst fishers was high.

The local co-operative spent a decade of trial and error and came up with a system whereby each year the top fishing spots were identified and agreed upon, and a roster was then made so that each fisher rotated through the fishing spots.

The system was governed by the fishers themselves. The fishery thrived. The conflict subsided.

A government official or private organisation could not have derived such a solution. The solution relied on the in-depth knowledge of the area of the local co-operative. It was made economically viable by the ability for the fishers, who were already on location, to self-enforce the rotation.

There are a several key aspects which can make the self-regulation of commons preferable to the privatisation or governance of these resources:

1. Users of a resource tend to have a breadth and depth of knowledge of its constraints and opportunities that would be extremely time and cost intensive to obtain externally. This knowledge may allow for the development of more effective resource management schemes than would be possible otherwise (Ostrom, 1990).
2. The time and cost implications of the enforcement of policies have often led to failed regulation by government and private organisations. Self-organising groups have the unique opportunity for self-regulation, with all actors playing the part of both user and regulator, thus reducing the complexity and cost of policy enforcement (Ostrom, 1990).
3. In many instances the removal of ownership from users of the commons takes away the sense of stewardship and leads to increased exploitation of the resource (McKean, 1998, Ostrom, 1990).

Of course, there are many instances where self-regulation of resources has failed. It is not enough to rely on self-regulation to manage the Earth System. Management theory suggests that there is not a single solution to managing the environment. It is a complex system and requires a flexible and adaptable approach that is likely to include governance, privatisation and self-regulation.

When considering the management of the Earth System, it is important to consider not only the type of management or decision-making framework (e.g. self-organised, privatised, governed, etc.) but also the scale of management (e.g. local, national, global, etc.). Formal attempts at managing the Earth System, particularly with respect to climate change, have thus far been predominantly at a global level, although there are notable exceptions such as C40 Cities which is an example not only of formal action at a lower scale, but also of self-organised management of the global commons (C40, 2017). While some form of global scale agreement will almost certainly be a necessary component of successful management of the Earth System, this is not the only scale that is important.

Global environmental problems are typically caused by a multitude of actions which take place at a far smaller scale (Ostrom, 2009, Kates and Wilbanks, 2003). Given the diverse nature of the causes of climate change, global or even national policies could miss many opportunities for emission reductions. Further, trust is often greater in local bodies than in national governments as local bodies are perceived to have more awareness of local conditions.

Small scale or local initiatives alone would of course be insufficient to manage a problem such as climate change as many opportunities to reduce emissions rely on decisions which can only be made at a larger scale (Kates and Wilbanks, 2003). One might also argue that there are already many small-scale actions taking place with limited global success.

4.3.2.1 Poly-centric management

Research into the governance of metropolitan areas has shown that while large-scale governance systems are an essential element in the efficient management of cities and metropolitan areas, small and medium scale components were also necessary. Ostrom draws parallels from this to climate change mitigation (2009). She suggests that there is no one solution for the management of the commons and that each case should be considered individually. In a background paper to the World Development Report for the Wold Bank, Ostrom (2009) proposed a polycentric approach for dealing with climate change, where a polycentric order is defined as:

> "*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*." (Ostrom, 1999)

Polycentric systems are characterised by multiple governing authorities at different scales, in contrast to a monocentric unit (Ostrom, 2010). The general system of rules is included as a mechanism to impart trust in the long-term benefits of the actions, and that others are contributing to the same goal.

There are many studies which support Ostrom's proposal e.g. (Neuvonen et al., 2014, Galaz et al., 2012c, Brondizio et al., 2009). Reports on global biodiversity management refer to the importance of action at all levels and across different decision making centres (Secretariat of the CBD, 2014, Secretariat of the CBD, 2006, Secretariat of the CBD, 2010). Agenda 21, the outcome of the 1992 Earth Summit, identifies public participation as a "fundamental prerequisite" for sustainable development. It proposes national government collaboration with local government and "major groups" (e.g., women and indigenous people) (United Nations Conference on Environment and Development (UNCED), 1992). Local Agenda 21 initiatives emerged throughout the world, some of which are ongoing today (Wittmayer et al., 2015).

A multi-levelled approach has proven successful in other applications. A*ggregated marginal gains* is the idea that if every possible trivial gain is made, these multiple little successes add up to provide worthwhile benefit. This has been used with high success to raise the British

Cycling team from underdogs to Tour de France winners in only 3 years. The concept has also been shown to be effective in driving improvement in healthcare (Meyer and Merry, 2017) (see Box 4.4). The healthcare findings are consistent with others' findings that quantifying individual environmental impacts helps to motivate people to reduce their consumption (Holmberg et al., 1999). Lorek and Spangenberg (2001) identified a need for actor-centric measurement as a means to change behaviour.

Ostrom made the point that management must occur at a scale that "can encompass the problem" (Ostrom et al., 1961). This concept has also been applied to designing sustainable cities where agglomeration economies are understood to be the basis of wealth creation and productivity gains due to the meaningful overlap of skills and integration of networks that are critical to the knowledge economy (Glaeser and Gottlieb, 2009, Graham and Dender, 2011, Trubka, 2011) . Agglomeration is about more than multiplying activities, it is also about the scale at which certain functions in society work best. Thus, by creating different scales or

Box 4.4: A polycentric approach to NZ healthcare

In response to the large numbers of falls reported annually to the NZ Health Quality and Safety Commission (the Commission) a programme was developed to reduce harm from falls. Rather than the traditional top-down approach, the Commission's approach was multi-layered. Support and guidance (or, "the general system of rules") comes from the centre. However, the implementation was flexible, focused on every individual context, and driven from those on the ground. Every clinician was expected to ask at every encounter with a patient, "How can this person be prevented from falling – and what can I personally do to achieve this?" The Commission found that providing feedback to the clinicians that allowed them to track their own performance and compare it to their counterparts was a very effective means of driving change. Recently, high levels of compliance with the local process indicators of the falls program have been matched with a statistically significant reduction in the rate of hip fractures (the national-level outcome indicator), which is a substantial achievement in respect of a clinical challenge known internationally to be difficult. While NZ healthcare may seem very distant to the management of our global environment, the learning outcomes of this example are highly relevant. Specifically, giving individuals the opportunity to determine the best method of achieving a specified outcome was shown to be very effective in driving change.

levels of agglomeration to measure human activity those functions can be better compared and transformations become possible.

4.4 Change Theory and Sustainability

Newman (2005) writes about the "magic" of sustainability. He describes the magic as an innovative solution which exceeds expectations. He muses that the magic most often appears a result of a new, integrative approach to problem solving that allows space for reflexive learning. Specifically, he suggests that when community values and visions overlap with government regulations and infrastructure, and business innovations – whether products or services, this is when the magic of sustainability can occur (see Figure 12).

An important element of this concept is that it brings together different timescales. The values and visions of a community are typically tied into culture and beliefs – which stretch over a long timescale. Parents have dreams for the future for their children, grandchildren and even great grandchildren. Government timescales are typically mid-term. Infrastructure projects such as rail systems and buildings are built to last over decades. Government strategies are often prepared with a 20 to 30-year view. On the other hand, governments often have high inertia and are slow to make change. Projects can be under consideration for decades prior to their implementation. In contrast, businesses operate rapidly, moving from one innovation to another. They can be agile and flexible. There is space for trial and error. Businesses have a very short-term focus. Stakeholders demand rapid payback. It is not uncommon for business decisions to be made with consideration only of the implications over the next few years. Corporate sustainability plans frequently have targets spanning less than a decade.

When these groups come together, businesses can begin to innovate with the long-term visions and aspirational goals of the community in mind. Governments can gain from the fast pace approach of businesses, while incorporating the long-term views of the community. When there is space to discover an overlap of common interests, the magic can occur.

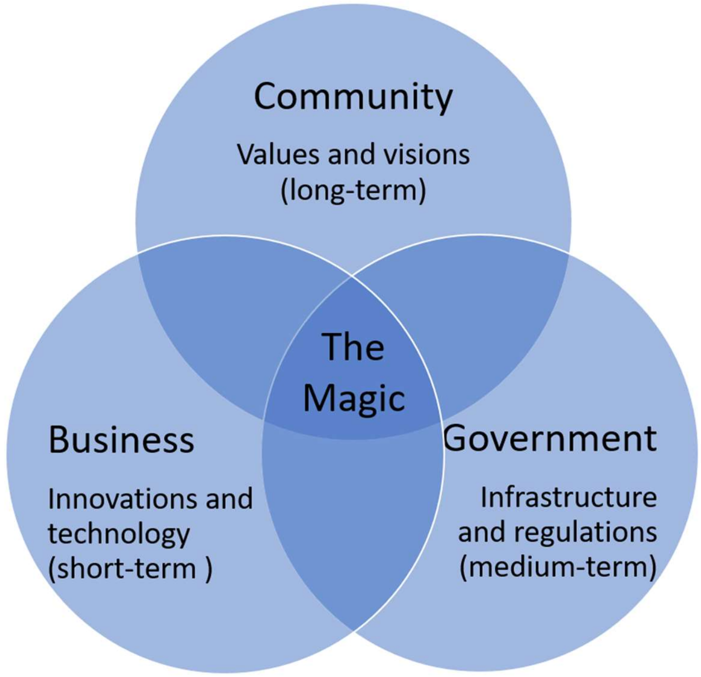

Figure 12: The magic of sustainability occurs when community, business, and government interests overlap (adapted from (Newman and Rowe, 2003)

This notion of using integration to obtain a result that is better than the sum of its parts is not new, nor is it limited in its success to sustainability applications. For example, “holistic design” is an architectural concept that has become popular over the last decade. Holistic design is synonymous with integrated design and occurs when all stakeholders are included in the design process from the outset. Innovative solutions borne out of such an approach can often achieve efficiencies that would be unlikely without the involvement of all parties from the start.

An integrative approach to finding solutions is just one component of change theory. In his book Tipping Points, Gladwell (2000) evaluates why some innovations generate change, while others with seemingly similar potential fail. He suggests that there are several common characteristics associated with successful innovations: *the law of few, the stickiness factor, and context.* The importance of context to drive behaviour change has already been discussed in Section 4.2. The stickiness factor relates to the message or product’s memorability, the ability to “stick” in one’s mind. The third factor, the law of few, is that social epidemics are led by a few key people. These people are commonly referred to in the literature as agents of change.

Agents of change, sometimes referred to as “local heroes” in sustainability circles, can be individuals operating in a community, CEOs driving change through business, or government officials who create change through their position in society. For example:

> Rosa Parks was an individual who by refusing to give up her seat in the white area of the bus, inspired community action that was a key component in the black rights movement in the United States.
>
> Winston Churchill took over the leadership of Great Britain during the second world war and encouraged the country to stand up to Hitler, a move that was instrumental to the Allied war effort victory in 1945.
>
> Elon Musk has been instrumental in accelerating the global transition to sustainable energy.

The power of the individual is lost in a top-down governance model that suggests that to persuade people to act for the greater good we must impose regulations. Global societal change such as the end of slavery, black rights, and women’s rights, have come about through collective bottom-up efforts at varying scales towards a singular goal.

Disruptive innovations are another important driver of change. Disruptive innovation is a term used to describe solutions that displace the status quo. Disruptive innovations often (though not always) leave past systems obsolete. Disruptive innovations almost always lead to systemic change (see Chapter 5). Uber is an example of disruptive innovation with systemic change; the most successful global taxi business does not own its fleet of vehicles. The digital camera is another example. Camera companies altered their business models from a per photo income model to a model where all the income needed to come from the sale of the cameras and accessories. Kodak, who first invented the digital camera, went out of business, as they updated their technology but did not update their system.

In summary, change theory highlights the importance of integration across sectors and time-frames. It also highlights the critical role of innovation, technology, and context. Finally, it confirms the importance of different scales of action, in particular the scale of the individual, in driving change.

Box 4.5: Disruptive Innovations

Disruptive innovators understand that demand is not based purely on cost. People want things for many reasons. Some disruptive innovations take a top down route – i.e. they are immediately superior solutions which are initially unaffordable, but the cost comes down over time because of demand. The Tesla vehicle is an example of an innovation that is likely to be a top-down, disruptive innovation. Some disruptive innovations are considered to be bottom-up – the solutions are initially inferior and unaffordable, but over time, become both superior and affordable. Photo-voltaic (solar) panels are an example of a bottom-up innovation. The best, most disruptive innovations which are superior and cheaper from the start are known as big-bang disruptions. Google maps is an example that made previous navigations obsolete almost overnight.

4.5 Poly-scalar Management of the Earth System

The three theories described above can be used to advance Ostrom's proposal for a poly-centric approach. Poly-centricity at its core is about multiple scales of governance (Ostrom et al., 1961) (Ostrom, 2010). Ostrom has identified the importance of different decision-making frameworks include self-organised initiatives, privatisation, and governance (Ostrom, 1990, Ostrom, 1988, Ostrom et al., 1994). Yet, her discussions about the benefits of a polycentric approach refer predominantly to the inclusion of local and regional scales of governance (Ostrom, 2010, Ostrom, 2009, Ostrom, 1999). Further, a poly-centric approach does not demand integration across different sectors, nor does it consider different timeframes.

As shown in this chapter, theories of behaviour, of commons management, and of change, point to the importance of an integrated approach - not only of different scales of governance from local to global, but also of different decision-making frameworks including self-regulation, privatisation, and governance, across different sectors of society from community, to business, and government, and of different time scales from the short term to long term.

I therefore propose a poly-scalar approach to managing the Earth-system. Such an approach would mean one which is:

integrative across different scales, sectors, and timeframes, that is not controlled by a single body, but which could be implemented through governance, privatisation, or self-organised *management, that is coordinated by a general system of rules which have different mechanisms at different centres of activity.*

There are many benefits of such a high-resolution approach.

The implementation of a global solution would be reliant on a high level of certainty of its efficacy which would most likely require costly and time intensive analysis and review. In a multi-scalar approach, initiatives could be rolled out immediately across the globe without the delays inherent in a coordinated top-down approach.

Numerous small-scale solutions provide the opportunity for trial and error, results of which could be fed back into the development of larger scale actions and policies (Ostrom, 1990, Kates and Wilbanks, 2003). Capturing lessons learnt from a wide range of approaches would facilitate a high rate of knowledge uptake that would be very time and cost intensive to emulate otherwise.

Integrative thinking that brings together local heroes, community values, national legislation, and business drivers may help to develop disruptive innovations that drive systemic change at multiple levels of activity. Continuing with the example of climate change, the solution will require changes at every level, from the day to day activities of individuals, families, and communities, to the policies and regulations of companies and nations. It is not the case that the effort at each level goes unrewarded. Benefits of mitigating climate change are seen at all different levels. For example, a household choosing to invest in insulation and energy efficient appliances will see long term payback through reduced energy bills; the inhabitants of a city in which the use of cars is minimised will all reap the benefits of the cleaner air.

Local communities and cities are in a position to identify specific opportunities for improvements that might not be obvious at a larger scale. It is easier to hold cities or nations (as opposed to individuals) accountable if they take on the role of a free-rider. A high-resolution approach that has a system of rules with the flexibility to be used transparently across so many scales of activity would help to build trust at all scales that others are working to the same end.

In the transport example, a nation may have targets to reduce transport-related impacts in order to meet international commitments. However it is most likely a city level decision to provide a comprehensive public transport solution and therefore give individuals the opportunity to make a lower impact transport solution (Newman and Kenworthy, 2015). At a local level, people would reap the benefits of less congestion, reduced noise pollution, and improved air quality. The decisions of the individuals, city planners, and national leaders would, together, contribute to the national and global targets.

Table 2 shows examples of different areas, scales, and sectors that would be encompassed in a poly-scalar approach.

Table 2: Examples of different areas of activity in a poly-scalar approach to Earth-system management

Scale:	***Areas of Activity:***		
Large	Global Community Groups: *e.g. IPCC, WWF*	Global Governance: *e.g. United Nations*	Multi-national Firms: *e.g., Unilever, Mars*
Medium	City – National Scale Community Groups *e.g. ACF, YCA, C40 Cities*	National, State, City Government	Medium sized businesses
Small	Households, Communities, Neighbourhoods	Local Government	Small businesses
Individual	Individuals, Local Heroes	PMs, Mayors, Local Heroes	CEOs, Sustainability Managers, Employees
Sector (time-frame):	**Community (long-term visions and values)**	**Government (medium-term focus)**	**Business (agile, short-term outlook)**

4.5.1 The Montreal Protocol – A successful example of top-down global governance or of a poly-scalar approach?

As previously mentioned, the Montreal Protocol is often used as an example of successful top-down governance. However, it could be argued that its' success lies in its' poly-scalar approach.

It was first recognised that some substances could, and were depleting the ozone layer in the mid-1970s (Chesick, 1975). In 1985 an article was published in Nature confirming that there was a repeating springtime hole in the ozone layer (Farman et al., 1985). The Montreal Protocol was first ratified in 1989 (UNEP, 2017a). In 2009 it became the first treaty to have universal ratification (UNEP, 2017b). Scientific evidence shows that the ozone hole is reducing (Solomon et al., 2016). Models predict that provided the Montreal Protocol continues to be followed, the hole will continue to recover (Solomon et al., 2016).

The hole in the ozone layer is a global scale environmental problem that is the result of a public bad (the pollution of the atmosphere with ozone depleting substances). On the face of it, it appears that the public bad was resolved through top-down governance – a global treaty for change.

However, there are some important factors believed to have contributed to the protocol's success.

- Prior to the development of the protocol, there were growing community groups lobbying heavily for the removal of the substances that were causing rapid sunburn amongst children in southern latitudes (Stocker L et al., 2012).
- The Montreal Protocol included mechanisms to target not only policy makers but also institutions who gained the most from these substances (Parson, 2003).
- The key manufacturers of the chemicals involved in the Montreal Protocol already had a preferable solution to the problem and therefore would not get in the way of regulations to ban their chemicals. It simply was a problem of governments making mechanisms to phase out their use in existing products like spray cans and refrigerants.

These show evidence of integration across different scales and sectors, the important role technology played, and the presence of change agents pushing community values and visions. The Montreal Protocol is an example of a poly-scalar approach to managing an Earth-system process.

4.6 Conclusion

Past theories led to the belief that privatisation or top-down governance were the only effective ways to manage shared resources. However, the latest scientific knowledge, from the fields of behaviour change, commons management, and change theory, suggests that an alternative approach would be preferable.

This chapter shows that there is a need for a poly-scalar approach to Earth-system management, that is integrative across different scales, sectors, and timeframes, that is not controlled by a single body, but which could be implemented through governance, privatisation, or self-organised management, that is coordinated by a general system of rules which have different mechanisms at different centres of activity.

The following chapters go on to discuss the general system of rules for such an approach. The rules would need to communicate the level of impact that humans can have without altering the Earth System in a way that can be applied using a poly-scalar approach. The next chapter is about measuring the environmental impacts of different scales of human activity against absolute, scientific limits, an important element of the general system of rules.

CHAPTER 5

Environmental Accounting, Absolute Limits, and Systemic Change

Abstract

We are currently operating outside of the Planetary Boundaries, global environmental limits which define a safe operating space for humanity. The order of magnitude of change required to live within the Planetary Boundaries is substantial. It is unlikely that we would be able to live within them without fundamentally altering the way humans interact with the environment; we need systemic change.

Accounting theory shows that standards or limits are needed to create serious change. Environmental accounting, the estimation and monitoring of past, present, and future environmental impacts from human activity helps to apply this theory to the task of managing environmental impacts. It has been instrumental in our capacity to manage the environment.

It is common practice for almost every country, many cities and regions, and many businesses, to track some of their environmental impacts against past impacts, benchmarks, and future targets. Estimations of future environmental impacts can be used to inform planning and decision-making help to manage and reduce the impacts of our activities. However, for most impacts, there are no existing mechanisms to put the results into the context of scientific targets or limits. This means that the end goal is unclear.

Incremental targets are frequently set against a previous benchmark or industry best practice. Such targets are arbitrary and invite incremental rather than systemic change. In contrast, absolute, scientific limits would enable decision makers to understand the magnitude of change required and to work towards systemic change.

A mechanism that allows current environmental accounting practices to be understood in the context of scientific environmental limits is needed. Such a mechanism would allow us to begin to understand how to live within the Planetary Boundaries.

5.1 Introduction

Accounting theory highlights the importance of measuring and monitoring assets and flows in order to make informed decisions. Governments, private organisations, and households alike make informed decisions and choices based on their knowledge of the state of their assets and of incoming and outgoing cashflow. Environmental accounting translates these insights from accounting theory to the management of environmental impacts.

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 (Biswas and Modak, 1999). 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 (Biswas and Modak, 1999).

The translation of EIA into environmental accounting – the practice of measuring and monitoring environmental assets, gains, and losses over time - followed quickly. Norway was one of the first countries to begin keeping formal environmental accounts. They identified their environmental assets – forests, fisheries, energy, and land and began to track the state of these in the early 1980s (Saebo, 1994). The Netherlands introduced the National Accounting Matrix which included environmental accounts in 1991 (De Boo et al., 1193, Biswas and Modak, 1999, BIS, 2012)

In response to the Rio Earth Summit in 1992, the United Nations developed the System of Environmental-Economic Accounting (SEEA) (UN, 1993). It was developed in collaboration with the World Bank, to assess the feasibility of using monetary accounting practises to assess natural resources. The most recent update – the SEAA Central Framework was adopted by the UN Statistical Committee as the first international standard for environmental-economic accounting (UN Statistics Division, 2018).

In the 1990s, new methods for assessing environmental impcts were developed such as the Ecological Footprint (Rees, 1992). Some of these are used to estimate the impacts of different scenarios to inform decion making e.g., (Global Footprint Network, 2014b). Today, environmental accounting refers to the practice of assessing past, current, and estimated future environmental impacts, and reporting the results over time, often against specified targets. These techniques continue to evolve and are the basis of this work though much more focussed.

This chapter begins by introducing two different types of change, systemic and incremental. This is followed by an overview of EIA methods, and the benefits and limitations of environmental accounting. The concept of absolute limits is then introduced. Accounting theory and carbon accounting are used to show why absolute limits are essential if we are to generate systemic change and be successful in managing human impacts on the environment.

5.2 Systemic vs incremental change

The conclusion from Chapter 3 was that humans should aim to live within the Planetary Boundaries (PBs) – environmental limits within which the risk of changing the state of the planet is low. We have already exceeded four of the nine PBs. These are not marginal transgressions. The current rate of species extinction is between 10-100 times the PB for biosphere integrity. The energy imbalance in the atmosphere is more than double the "safe" level for climate change. More than twice the PB levels for phosphorous and almost three times the PB levels for nitrogen are being released into the environment each year. Almost one billion hectares of forest needs to be replanted – an area approximately the same size as the United States – to return to the PB for land use.

To meet the needs of the projected (and current) global population without reducing Earth's capacity to support the way of life that many of us in the richest nations have now come to expect, is not a small undertaking. It may not be possible at all. It is unlikely that it will be possible without fundamentally rethinking the way humans operate – i.e., without systemic change.

Systemic change means change to the entire system, as opposed to parts of the system (Oxford Dictionary, 2018). It is also referred to as transformative or transformational change e.g., (Termeer et al., 2017, Seijts and Gandz, 2017). Incremental change on the other hand refers to small changes that do not usually require the whole system to be changed. Incremental change does not threaten existing models and frameworks. The implications of incremental change can usually be predicted with a reasonable level of confidence. For these reasons, incremental change is often the preferred path for decision makers. Systemic change is not simply a larger increment of change, it is a different type of change altogether. Incremental change does not usually lead to systemic change.

Henry Ford, who was the first to mass produce automobiles, purportedly said "If I had asked people what they wanted, they would have asked for a faster horse". Too often, efforts towards managing the environment focus on reducing impacts – the faster horse or incremental approach. Consider modern cars for example:

In light of the increased understanding that people must emit less carbon dioxide to the atmosphere, many companies have worked hard to improve the fuel economy of their petrol and diesel vehicles – i.e., to reduce the carbon dioxide emissions per kilometre of travel. The greater the efficiency becomes, the harder it becomes for the companies to find ways to further improve it. The invention of the electric car is game changing. It puts the whole system of petrol vehicles, petrol stations, and fossil fuel transport in question. Suddenly companies who have invested so much time and energy into improving the efficiency of their petrol engines, are competing with zero emission vehicles.

Electric cars were invented before the petrol engine (Bellis, 2017) (see Figure 13). However, the first modern electric car that could compete with modern petrol vehicles – i.e., to drive at comparable speeds and over 100+ kilometres in a single charge – the Tesla Roadster, was not released to the public until 2008 (see Figure 13). The Nissan Leaf, the first mass market electric vehicle produced by a major manufacturer, was released in 2010. Only eight years later, China, India, France, Britain, and Norway are working towards phasing out petrol and diesel cars altogether (Gray, 2017). The system is changing. Car companies who do not quickly make the transition to electric vehicles risk going out of business[12]. In contrast, companies which had the foresight to develop electric vehicles have also had a head start in thinking about related business opportunities such as charging stations and in-home charging equipment. The invention of electric cars is an example of disruptive change (see Chapter 4) that is likely to lead to systemic change. However, the story does not end here.

There are experts who predict that the role of the automobile needs to and will diminish e.g., (Newman and Kenworthy, 2006, Newman and Kenworthy, 2015). These authors have identified that cities built around cars are less amenable to their inhabitants than those which are not. They have shown that increasingly, cities are shifting towards alternative modes of transport. The authors propose alternative, more efficient uses for land area that is currently used for roads such as city farms.

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[12] Elon Musk has made the patents from the Tesla vehicle available to anyone MUSK, T. 2014. *All Our Patent Are Belong To You* [Online]. Tesla. Available: https://www.tesla.com/en_NZ/blog/all-our-patent-are-belong-you [Accessed 22 April 2018]. In the case of the electric vehicle companies who have been slow to transition may thus still be able to keep up with the transition to electrical vehicles. This is an unusual occurrence, but a good example of how an individual can act as a change agent to achieve global change (see Chapter 4).

A shift away from automobile dependence is an example of true systemic change. This is one example of the extent of change that may be required to end the global environmental crisis.

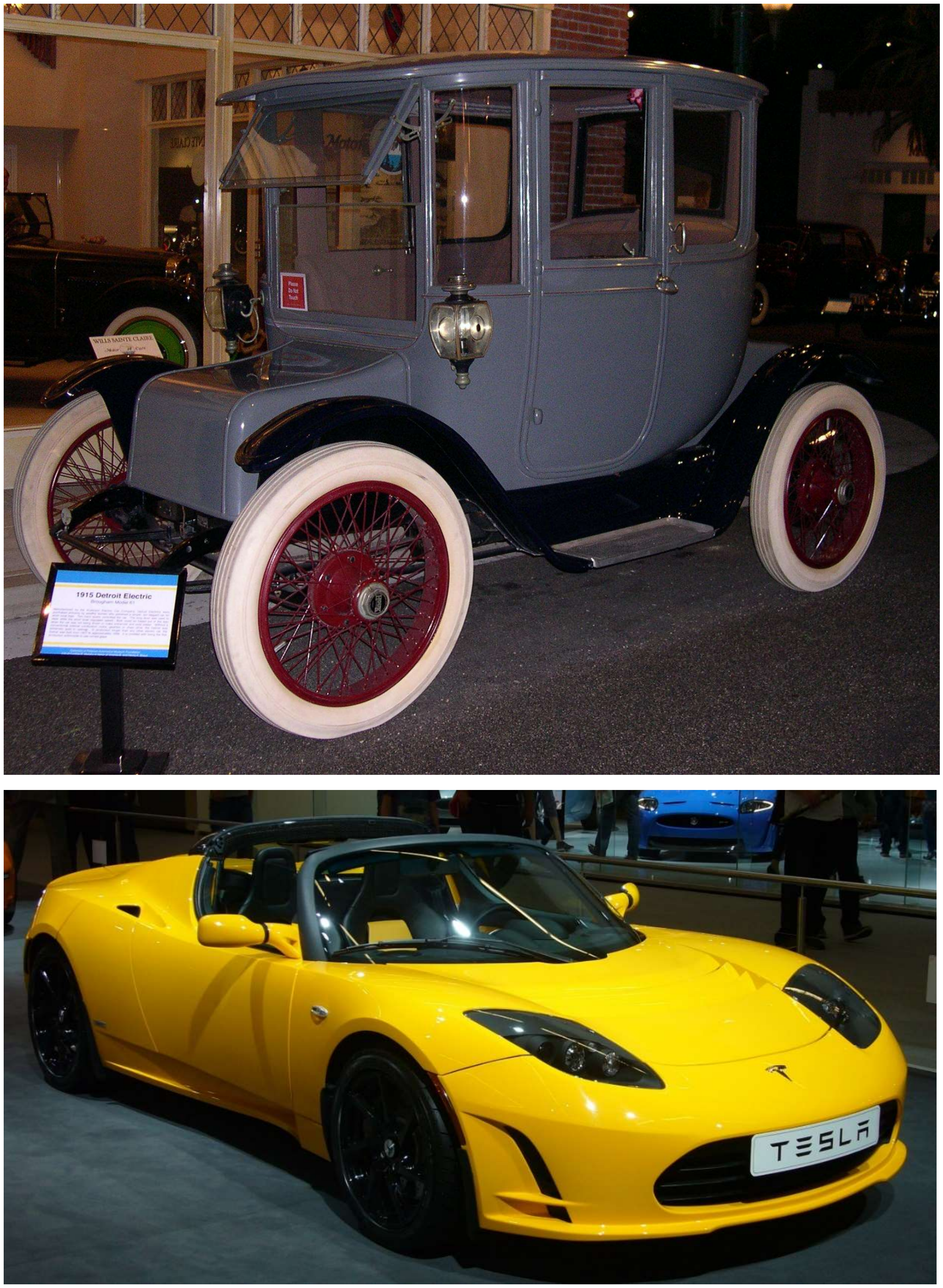

Figure 13: 1915 Detroit Electrical Vehicle (top) and Tesla Roadster 2.5 ((Sfoskett, 2005, Overlaet, 2011) (CC BY SA 3.0[13]))

[13] CC BY-SA 3.0: Creative Commons License allows reuse with appropriate credit

The fundamental problem with incremental targets is that they can often be met with incremental changes, at least to begin with. This means that a lot of effort can go into improving the efficiency of fundamentally inefficient systems. Innovative solutions can be missed with such an approach (Akenji et al., 2016). If car companies considered the magnitude and breadth of change required to transition into a sustainable future – they might conclude that the demand for any form of private vehicle is on the decline, or is likely to be soon, and target their efforts at innovative semi-private or public transportation solutions.

There is a phenoMe-NOn known as the rebound effect, or moral licencing, which can occur as a result of incremental reductions to environmental impacts. For example, following the installation of photo-voltaic (solar) panels on a house a surge in electricity consumption is often found. This is because the occupants feel that they have made good steps towards reducing impacts on the environment and can therefore relax about sustainable habits such as turning off unneeded lights. This phenoMe-NOn is typically association with incremental improvements rather than systemic change (Arvidsson et al., 2016, Hertwich, 2005, Kojima and Aoki-Suzuki, 2015).

To live within the Planetary Boundaries, systemic change is needed.

5.3 Environmental Impact Assessments – A History

In the early days of environmental impact assessment, this constituted measuring the state of the environment. For example, the total area of forest and the number of trees per meter squared might have been used to monitor the state of a forest.

Over time, people began to consider not only the state of the environmental assets, but also the environmental flows, which effected the state of the assets (like cashflow in economic accounting). In a forest, this could have meant monitoring and recording the number of trees planted, the number of trees extracted, the amount of wood produced or wasted, the amount of fertiliser being applied and so forth. The SEEA-Central Framework now sets out how to monitor environmental assets and flows so that these are monitored in a consistent way between different nations (UN, 2014).

In the early days of environmental accounting, the environmental limits were often clear. In the example of a forest, people understood rates of growth for different tree species and could thus determine the maximum rates of extraction that could occur without diminishing the forest. However, as we got better at estimating impacts, the limits became less obvious. For example, we know now that releasing sulphate into the atmosphere contributes to air pollution. Yet, if only a small amount of sulphate was released, the change to the atmospheric conditions would be negligible. No one has determined a safe limit for local or global sulphate emissions. This is true for many environmental flows with a few notable exceptions such as the release of carbon dioxide into the atmosphere.

Despite not having upper limits, 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. There are many types of environmental impact assessments e.g., Life-Cycle Assesment (LCA), environmental footprint assessment, and Material Flow Acounting (MFA). LCA and environmental footprint assessment are two of the most commonly used typs and are therefore described in more detail in the following sections.

5.3.1 Life Cycle Assessments

LCA is the process of identifying and tabulating all resource and waste streams from the extraction of raw materials, the production of the product, the use over its lifetime, the transportation of the raw material and the product, and finally the disposal.

The earliest studies, which were not then called life-cycle assessments, but are now considered to have been partial life-cycle assessments, date back to the late 1960s and early 1970s (Guinée, 2012). These assessments were typically undertaken to compare different packaging options. Initially, only energy consumption was considered. Later, resource use, waste, and emissions were also taken into account. (Guinée, 2012)

Until the 1990s, LCAs were performed using different methods, terminologies and approaches. In 1994 the International Organisation for Standardisation (ISO) produced the first international standard for life cycle assessments: ISO:14040:1997 Environmental management - Life cycle assessment - Principles and framework (ISO, 1997). This standard enabled a much greater level of consistency, robustness, and transparency in life-cycle-assessments.

Many environmental claims made about products pertain to only a single aspect of a product’s environmental impacts. For example, cars are often compared to one another for their fuel economy. Yet a car with better fuel economy may or may not have lower impacts over its lifetime. The overall impacts depend on a multitude of factors for example, the amount of raw materials used, the efficiency of the manufacturing processes, or the overall lifespan of the car. LCA allows the big picture of environmental impacts to be better understood. LCAs take every aspect of a products environmental impact into account thus allowing a far greater resolution for comparing the different impacts of a product or service.

Moreover, LCA includes a mechanism with which to weight and aggregate the different impacts into a single score so that overall impacts of one product can be easily compared to another. There are three major limitations of LCA:

1. To do a formal LCA assessment requires vast amounts of data that can be costly in both resources and time to aquire (Kirchain et al., 2017).
2. Aggregating different environmental impacts into a single score is imprecise and can give meaningless results (Kalbar et al., 2017).
3. Without aggregating results into a single score, the results of LCA can be difficult to communicate to the lay-person (Kalbar et al., 2017).

The LCA community are active in looking at both product and organisation level impacts. However, the limitations described above have led to a relatively poor uptake of LCA by businesses despite the depth of detail an LCA can provide (Kalbar et al., 2017).

5.3.2 Environmental Footprints

At approximately the time that LCA methods were being formalised into ISO standards, the concept of the Ecological Footprint was published (Rees, 1992). An Ecological Footprint (EF) is a measure of the natural capital used for or by a system (e.g., a person, group, or product). The results are expressed in a proprietary unit – global hectares (gha). Global hectares are a weighted unit of area to allow different land types to be compared for equivalent environmental value. For example, 1 ha of forest land was considered equivalent to 1.2 gha in 2006 (Valada, 2010), i.e., 1 ha of forest was estimated to be 20% more productive than a world average hectare (Galli et al., 2007, Monfreda et al., 2004). The EF of a product, person, or jurisdiction can be compared to the corresponding biological capacity (biocapacity). Biocapacity is a measure of available natural capital, also expressed in gha.

The EF does not account for all human impacts; however the authors attempted to capture all impacts which compete for space in this metric (Galli et al., 2014). The amount of each land type (see Table 1) used for a given activity is tabulated to determine the total EF of the activity. CO_2 emissions are included in the EF through an equivalent forest area – the area of forest that would be needed to absorb that much CO_2.

Table 3: Biocapacity and Ecological Footprint Land Categories

Biological Capacity	Ecological Footprint
• Cropland • Grazing land • Forest land • Fishing ground • Built up land	• Cropland Footprint • Grazing Footprint • Forest Product Footprint • Fish Footprint • Carbon Footprint • Built up land

The Ecological Footprint Atlas states that the EF is not intended to be a standalone sustainability indicator (Ewing et al., 2010a). The EF does not account for:

1. Availability or depletion of non-renewable resources.
2. Inherently unsustainable activities (for example wastes which the biosphere has no assimilative capacity for, such as the release of heavy metals, radioactive compounds and persistent synthetic compounds).
3. Environmental management and harvest practices.
4. Land and ecosystem degradation (yield factors do not take into account sustainability of practices).
5. Ecosystem disturbance or resilience of ecosystems.
6. Use or contamination of freshwater.
7. Non-CO_2 greenhouse gases.

Further, the authors have identified key limitations of the framework as:

- Aggregation of different land types giving the impression of more equivalence between different land types than is realistic;
- Accuracy is limited by the quality of datasets, many of which are incomplete and do not include confidence limits;
- The methodology leads to underestimation of the extent of impacts.

Notwithstanding the above, the concept of the Ecological Footprint quickly became very popular. EFs for small scale activities are often reported in terms of the number of Earths that would be needed to support the activity at a global scale. For example, my own impacts can be reported as "2.2 Earths", i.e., if everyone lived like me we would need 2.2 Earth's to support this. This straightforward and very visual communication of impacts is one of the key elements of the EF that lead to its mainstream acceptance. There are online calculators with which individuals can estimate their own footprint (Global Footprint Network, 2014b). There is a formal methodology for calculating national Ecological Footprint accounts (Ewing et al., 2010b). Accounts have been calculated for most countries and these are updated each year (Global Footprint Network, 2011).

The EF spawned many other footprint concepts including the water, carbon, and nitrogen footprints. Each footprint measures a specific impact of a person, group, activity or product. The results can be expressed in a variety of units such as mass, volume, or area. In a review of footprint analysis tools, Cucek et al. (2012) identified 31 different environmental footprints.

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 of an activity. However, the calculation process varies between footprints and few footprint indicators are regulated by International Standards Organisation (ISO) standards.

Footprints have been criticised for assessing only a single element of the environmental impacts of an activity. Some authors argue that footprints should not be considered as wholistic measures of environmental sustainability (Laurent and Owsianiak, 2017b). However others argue that the benefit of footprint assessments is that the results are easily communicated to the general public which is an important aspect of understanding environmental impacts (Ewing et al., 2010a). The issue of single environmental impact indicators is being addressed by several scholars through the use of footprint families e.g., (Fang, 2015b, Fang, 2015a, Fang et al., 2014, Galli et al., 2012)

5.3.3 The benefits of Environmental Accounting

Without environmental accounting, it can be very difficult to determine whether one activity, product, or behaviour is better or worse for the environment than another. Almost every trip to the supermarket, I find myself faced with the same problem – should I buy the tin of local – Australian grown – tomatoes, or the organic tomatoes that are grown and tinned in Italy and then imported. I still do not know which has less impact on the environment. It would take a substantial amount of work to determine the answer. Even if the tomato companies reported their water, carbon, and nitrogen footprints, or made a full set of LCA data available for the two products, the answer may still be unclear.

To add even more complexity, the way we purchase things also changes the overall impacts. If faced with the option to drive across town to a farmer's market where I could buy local, organic, and fresh tomatoes instead of tinned tomatoes I might decide that the impacts of driving across town would render this a false economy. A study was done in Sweden where the greenhouse gas emissions associated with different groceries were estimated. What was interesting in this graph is that the difference in impacts from local and seasonal food compared to the average bag of groceries was very similar to the difference in impacts between travelling 20km per week for groceries compared to 40km. The single greatest impact reductions were achieved through the decision to limit the purchase of beef.

Thus, by measuring and understanding the environmental impacts of different decisions, humans are more able to make informed decisions about our interactions with the natural world. However, this information needs to be provided in a manner which can be distilled by the lay person.

5.3.4 Production versus Consumption Accounting

As with any form of numerical modelling, the usefulness of the model depends greatly on the way the model is used. One key distinction between environmental accounts is whether they are considering the impacts related to consumption by a population, or related to the production within a defined area (Wiedmann, 2009). Both consumption and production accounts provide important and useful information. However, a common mistake in interpreting the results of environmental accounts is to use production accounts to derive consumption data. For example, national production accounts are frequently reported in per-capita figures, and compared to per-capita data for other nations. Given the global distribution of energy, food, and other products and services, this sort of comparison provides very little meaningful data. It stands to reason that impact of a net-exporting country, such as Australia or New Zealand will have higher production impacts per capita than a net-importing country such as Denmark or Singapore. This is not to say that Australian's and New Zealanders do not consume more than the Danish or Singaporeans. It is quite possible that they do. The problem is that production accounts do not help us to answer this question.

5.4 Absolute Sustainability

Environmental accounting allows humans to take responsibility for managing our impacts on the environment. It is now possible to estimate ahead of time what the environmental impacts of different decisions might be. While the accuracy of such estimations is limited, these estimations can be useful to inform decision making, planning, policy and legislation.

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 almost always based on improvements to the status quo or a past environmental state, rather than a desired future state founded in science (Akenji et al., 2016). Existing environmental assessment tools have been identified as lacking in suitability to inform society regarding environmental matters because of this lack of science-based targets or limits (Laurent and Owsianiak, 2017a, Akenji et al., 2016).

The Kyoto and Paris agreement targets are an example of this. Most of the targets are set based on percentage reductions from a past benchmark – typically 2005 or 1990 levels of emissions. It is arbitrary how far below 1990 or 2005 emissions levels a countries' emissions might be. Scientific methods can be used to predict with a reasonable level of confidence how many emissions of greenhouse gases we can afford globally while remaining below a given temperature target. It would be possible from this prediction to set a global, science-based target for emissions and then negotiate shares of this global budget. Of course, this would not resolve the difficulties of negotiating shares. However, with a clear target laid out, so too is the basis for systemic change.

Incremental targets can lead to missing opportunities for systemic change (Akenji et al., 2016, Sandin et al., 2015). Incremental improvements are the basis of most personal and policy change (Newman et al., 2017) and the importance of these should not be overlooked. Systemic change can sometimes be achieved through incremental action. However, without understanding the end goal, incremental improvements are unlikely to lead to systemic change. To live within the Planetary Boundaries, reducing GHG emissions and designating protected zones to safe-guard habitats might be necessary but will not be sufficient.

The idea of "absolute sustainability" or "absolute limits" refers to the idea of limits which are at a point that there are no longer negative impacts on the environment. Quantifying the point at which this occurs and being able to compare this to current impacts is considered by many to be critical in the management of human impacts (Akenji et al., 2016). It is believed by many experts that absolute limits will be needed to drive the systemic change necessary to transition to a sustainable future (Bahadur and Tanner, 2014, Pelling et al., 2015). Others recommend that a sustainable future should be defined by absolute environmental limits rather than efficiency improvements from the status quo (Akenji et al., 2016, Fang et al., 2014).

In financial accounting, people do not make decisions based only the state of one's assets and rate of outgoing cashflow compared to a benchmark or industry standard. This information is informative, but grossly lacking as the basis of financial management. An understanding of the maximum available cashflow is fundamental to managing accounts. To make informed environmental choices, governments, business, and individuals need to understand the maximum environmental capital available to them.

5.4.1 Absolute Limits and Ecological Footprints

The Ecological Footprint, introduced earlier in this chapter, compares impacts to biocapacity (Global Footprint Network, 2014a). This is taken to be a scientific, absolute limit by many who use it. In some ways it is. Global biocapacity is the total biologically productive land on Earth. It is a function of both size and productivity and thus changes from year to year. It is currently approximately 12billion global hectares (Global Footprint Network, 2012, Hoekstra, 2009, Vale and Vale, 2013).

The problem with using biocapacity as an absolute limit, is that this is the total resource bank of biological material for all species – not just humans. There is no sub-limit for human appropriation of the total biocapacity. As discussed in Section 5.3.2, EF terminology uses a number of Earth's to communicate impacts. This implies that a footprint of "one Earth" should be the target. This is perhaps a reasonable intermediary target for those of us in high income countries or with high consumption lifestyles as human impacts are currently substantially higher than this at a global scale. However, a footprint of one Earth would mean that all 12Ggha of global biocapacity is appropriated by humans. Whether or not this seems a selfish approach, it is certainly not a sustainable one, as humans rely so heavily on ecosystem services for survival. Further, it is critical ecosystems such as the Amazon rainforest that have provided such resilience for the Earth system to remain in a Holocene-like state.

There is no consensus in the literature as to an appropriate "biodiversity buffer" – the amount of biocapacity that should be retained for the maintenance of the Earth System. Galli et al (2014) propose the use of EF as an indicator for biodiversity but do not suggest a limit. Numerous studies have proposed a "biodiversity buffer", i.e., the amount of biocapacity which should be retained for biosphere integrity as part of the EF. The estimates range dramatically from 1% (Fahrig, 2001), 10-25% (Wackernagel et al., 2002, The Brundtland

Commission, 1987), 75% (Margules et al., 1988), to 99% (Fahrig, 2001). The limited examples where real case studies have been used to derive figures for a biodiversity buffer align at a value of around 45% (Soulé and Sanjayan, 1998, Margules et al., 1988). It should be noted that both studies found better results from a greater buffer, but at this level each species or community was represented more than once, a description approximately comparable to a maximum extinction rate.

5.5 Carbon Accounting – Environmental Accounting with Absolute Limits

Carbon accounting (or GHG accounting) is the most widely used form of environmental accounting. Carbon accounting refers to the practice of measuring and reporting emissions of CO_2 and sometimes other GHGs. The important difference between carbon accounting and other environmental accounting practices is that the results can be easily compared to global limits.

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 wide spread understanding of what is a relatively complicated scientific problem.

Individuals can calculate their "carbon footprint" – the amount of CO_2 released due to the activities of the individual. Formal GHG accounting protocols have been developed for nations, cities, and products and services e.g., (Fong et al., 2014, Greenhalgh et al., 2005). 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 the importance of limits. Different scales and types of emissions management are taking place across the globe. These efforts at every scale have already led to some success. Economic growth has been decoupling from greenhouse gas emissions since 2000 and in 2017 we are starting to see a levelling off and even a drop in fossil-fuel consumption and greenhouse gas emissions (IEA, 2017). For the third year in a row, population and GDP have increased while global CO_2 emissions have remained constant or declined (Newman, 2017c). However, the management of carbon dioxide emissions is not yet a truly poly-scalar approach. There is an absence of a clear set or rules. Targets for carbon dioxide emissions vary greatly. The Paris Agreement has a target of limiting warming to 1.5℃. The Planetary Boundary for carbon dioxide is an atmospheric concentration of 350ppm. The IPCC have proposed a pathway to phase out emissions by 2100. Without a clear understanding of the global budget of CO_2 emissions, the approach to managing CO_2 emissions is still somewhat piecemeal. A poly-scalar approach with clearly defined global targets will help increase the trust that efforts at every scale will make a difference to the end goal, and that others are working towards the same end.

If we hope to manage the Earth System to within the PBs, results of environmental impact assessments should be compared to absolute limits rather than incremental targets. We can use such an approach to drive systemic change.

5.6 Conclusions

The science of measuring and estimating environmental impacts that have occurred or may occur in the future because of human activity is very advanced. The key limitation of these measurements is that the results are usually not able to be compared to scientific limits. In order to better manage the environmental impacts of human activity, a mechanism to compare the results of environmental impact assessments to absolute limits is required. This is the basis of the research reported in this thesis. The following chapter shows how there is a disconnect between the findings of Chapters 2, 3, and 4, and introduces the topic of my research that addresses this gap.

CHAPTER 6

Resolving the Disconnect between Earth System Science, Management Theory, and Environmental Accounting

Abstract

The opportunity to use the Planetary Boundaries to inform policy, behaviour, and environmental management has been highlighted by several authors. Some have identified the prospect of using them in a multi-level approach. Others have recognised the potential to connect them to environmental accounting frameworks. There have already been at least six adaptations of the Planetary Boundaries: two connecting them to environmental assessment systems; the others, adapting them to form the basis of national or regional environmental accounts.

However, the Planetary Boundaries were not designed to be scaled, or to be related to human activity. They were intended as indicators of the scale and urgency of the problem, not as a guide to resolving it. This is apparent in the adaptations. Each adaptation has been a substantial piece of work – it is not a simple task to apply the PBs to different scales. There is little consistency between the metrics used in each of the adaptations which means it is difficult to compare one to another. Further, each adaptation targets one specific scale of activity; it would not be straightforward to apply any of these adaptations to other scales.

Insights derived from environmental accounting theories can be used to understand and resolve the disconnect between the Planetary Boundaries and the management of environmental impacts. The European Environment Agency Driver-Pressure-State-Impact-Response framework shows how different environmental indicators can be categorised. For indicators to scale and relate easily to human activity, the Pressure category of indicators are required. However, the Planetary Boundary indicators are not of a uniform category. Some are Pressures, most are States or Impacts. State and Impact indicators are not easy to scale or to relate to human activity.

There is no current mechanism to bring together environmental accounting practices and the Planetary Boundaries in a way that enables a poly-scalar approach to Earth-system management. For global limits to be accessible and actionable they need to be translated

into a uniform set of Pressure indicators. This is the basis of this thesis. The Planetary Quotas and the Planetary Accounting Framework aim to address this gap.

6.1 Introduction

The previous chapters in this section of this thesis introduced the Planetary Boundaries and presented two important insights derived from management theory and environmental accounting. Chapter 3 made the case that it would be prudent for humanity to aim to live within the Planetary Boundaries, as these are global environmental limits within which the risk of changing the state of the planet is low. Chapter 4 presented the case that management theory showed that there was a need for a poly-scalar approach to managing impacts on the planet. Chapter 5 used accounting and environmental accounting theories to show that scientific limits need to be applied to existing environmental assessment frameworks to enable systemic change.

The problem is that the Planetary Boundaries cannot be used in a poly-scalar way. Nor can they be used as the scientific limits for environmental assessment framework. This chapter uses further insights from environmental accounting to explain why, and to show what is needed to translate the Planetary Boundaries into a framework which is more accessible.

The chapter begins by introducing the previous adaptations of the Planetary Boundaries for use in policy and environmental management applications. It continues with a critical analysis of these, to demonstrate the limitations of the PBs for use in this manner. The Driver-Pressure-State-Impact-Response (DPSIR) is then introduced and used to explain why the PBs do not translate easily to policy and environmental management applications. The chapter concludes by making the case that the PBs should be translated into a uniform set of limits in Pressure indicators in order to make them more accessible.

Figure 14 shows how the Planetary Boundaries, and the insights from this chapter as well as Chapters 3 and 4 can be combined to develop the Planetary Quotas.

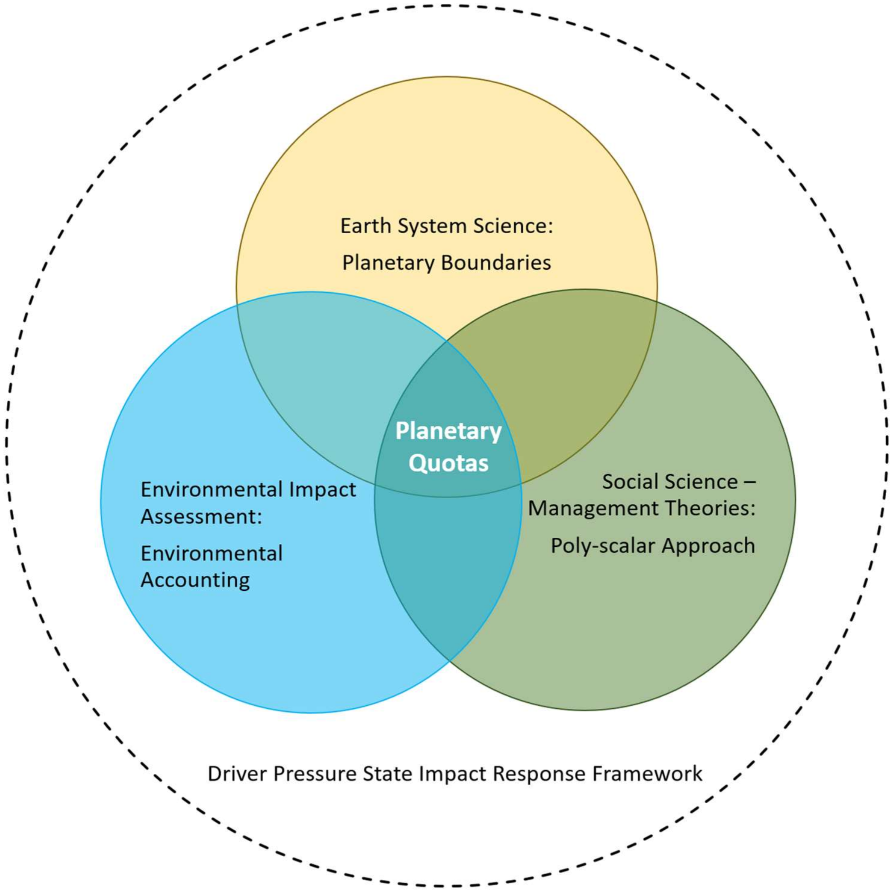

Figure 14 The Planetary Quotas bring together the latest advances in Earth System science (the Planetary Boundaries), Environmental Impact Assessment (Environmental Accounting), and the social science of management theories (a Poly-scalar Approach) using the Driver-Pressure-State-Impact-Response framework

6.2 Adapting the Planetary Boundaries

The first publication of the PBs discussed only global limits (Rockström et al., 2009a). One of the key additions in the 2015 update was the inclusion of regional limits for many of the Boundaries, in acknowledgement of the importance of changes at regional and local levels on the global functioning of the Earth System(Steffen et al., 2015).

Several authors have highlighted the opportunity for the Planetary Boundaries to reform environmental governance at multiple scales e.g. (Galaz et al., 2012c, Cole et al., 2014, Akenji et al., 2016, Galaz et al., 2012a). There are at six documented adaptations of the Planetary Boundaries for use as the basis of environmental accounts. These are summarised in Table 4. Three countries (Swizerland, Sweden, and South Africa) have used the Boundaries to develop national targets (Nykvist et al., 2013, Dao et al., 2015, Cole et al., 2014). The

European Union has new regional targets based on the PBs (Hoff et al., 2014). The final two adaptations are proposals for the use of existing environmental assessment tools – environmental footprinting and Life Cycle Assessment (LCA) – to compare impacts of human activity to the planetary boundaries (Fang et al., 2015a, Sandin et al., 2015). Table 4 lists these adaptations with a brief description of the approach used to adapt the PBs for each application.

Table 4: Adaptations of the Planetary Boundaries

Purpose	Approach	Reference
Determining national limits for Switzerland	Scaling limits using a top-down approach based on equal per capita share for past, present, and future generations	(Dao et al., 2015)
Determining national limits for Sweden	Scaling limits using a top-down approach based on equal per capita share	(Nykvist et al., 2013)
Determining national limits for South Africa	Bottom up approach based on national resources	(Cole et al., 2014)
Determining regional limits for the EU	Top-down approach based on equal per capita share	(Hoff et al., 2014)
Linking to environmental footprint assessments	Intermediate metrics to link top-down and bottom up.	(Fang et al., 2015b)
Linking to life cycle assessments	Relating impact categories from LCA to PB metrics	(Sandin et al., 2015)

Each of these adaptations is described in more detail below.

6.2.1 National Limits for Switzerland

Dao et al. (2015) converted 5 of the nine PB limits to national level limits. They excluded four PBs with the following justifications:

- Ozone depletion – ozone depleting substances are being phased out under the Montreal Protocol.
- Water – lack of evidence of a global limit.
- Aerosols and novel entities - lack of rationales from which to set limits.

The Swiss study is based on an equal per capita share for past, present, and future generations (Dao et al., 2015). It is the only adaptation of the Planetary Boundaries to include a temporal element in the derivation of a share of the safe operating space.

In the derivation of national limits, the authors of the Swiss study began by selecting new control variables for each Earth System processes. Where possible, they selected indicators which describe the state of the environment. Other types of indictors were selected only when they found specific justification to deviate, for example the lack of a suitable state indicator. They then determined global limits for the control indicators selected – noting that some of these were annual limits, while others were limits over time. Finally, they calculated the Swiss share of each global limit.

Of particular note is their limit for CO_2 emissions. The Swiss CO_2 threshold is set based on a warming limit of 2°C. The authors acknowledge that this does not correspond to the safe operating space but suggest that this figure is more congruent with existing indicators used in Switzerland. They argue that a more stringent condition would have little effect due to the already significant challenges involved in remaining below 2°C.

Another unusual element of the Swiss approach is their temporal allocation of CO_2 emissions. Accounting for projected population growth, they find that this gives 1.7tCO_2e per capita, per year (until 2100), a limit for the world of 12.3GtCO_2e in 2015. In contrast to typical pathways that show reducing CO_2 emissions over time, the way that the authors have determined the limits gives the lowest limit in 2015, with the global limit increasing with time due to increasing population. Their overall budget is based on IPCC projects of a 50% chance of remaining below 2°C. This gives an average of 15.5GtCO_2e per year until 2100. What is unusual in this approach is that the annual budget is therefore less in the first year than in 2100 because of the increasing population.

6.2.2 National Limits for Sweden

Nykvist et al. (2013) converted four of the PBs to national limits – PBs for climate change, water, nitrogen, and land-use. They omitted the PB for novel entities because of a lack of detailed and accurate data. They did not propose limits for biodiversity loss, ozone depletion, phosphorous, or novel entities but identified alternate indicators to assess these at a national level. They did not propose an indicator or limit for the PB for aerosols.

Like the Swiss limits, the Swedish limits were calculated based on an equal per capita share. However, the Swedish limits did not take into account time or population growth. Unlike the Swiss limits, the Swedish adaptation prioritises control variables pertaining to environmental flows (such as emissions of CO_2 or consumption of water) rather than environmental states.

It is interesting to compare the Swedish and Swiss limits for CO_2. The Swiss per capita limit is 1.7GtCO_2e per person per year. The Swedish limit is 2tCO_2 per person per year. Initially these values may seem very close. However, the Swedish limit is far more lenient as it considers only emissions of CO_2 whereas the Swiss limit of CO_2 *equivalent* also includes emissions of all other GHGs (Dao et al., 2015).

6.2.3 National Limits for South Africa

Cole et al. (2014) took a very different approach to adapting the PBs to national indicators for South Africa. They assessed each PB against the following criteria:

- Is this relevant at a national scale?
- Does the set of dimensions include the main environmental and social concerns in South Africa?

Where the response to both questions was positive they then set about determining the most appropriate indicators based on the availability of data and a means to determine a national level limit. The limits they proposed were not based on a global share of the PBs. They were determined using a bottom up approach. Their limit for biosphere integrity is *no endangered or critically endangered ecosystems*. This is difficult to compare to the PB of a maximum extinction rate of 10 species per million species per year. It is possibly a more stringent limit.

6.2.4 Regional limits for the EU

Hoff et al. (2014) take yet another approach. They compare European footprints to the Planetary Boundaries and propose Europe level limits for each footprint.

In the footprint assessment they consider:

- Material footprint;
- CO_2 footprint;
- Water footprint;
- Land footprint; and
- Biodiversity footprint.

The material footprint has no associated PB. It is worth considering that in order to operate within the PBs it is likely that the global material footprint would need to shrink substantially. This is discussed in Chapter 17. The CO_2 footprint is compared to the limit proposed for Sweden of 2tCO_2 per capita (Nykvist et al., 2013) rather than the Planetary Boundary. Of the footprints assessed, only the water and land footprints were directly compared to the PBs. Although there is a PB for biodiversity, the control variable used to assess the state of biodiversity in the EU cannot be compared to the PB control variable.

6.2.5 The FB-ESA Framework

Fang et al. (2015a) proposed a framework for the conversion of the Planetary Boundaries to footprint indicators, the "Footprint-Boundary Framework for Environmental Sustainability Assessment" (F-B-ESA). The authors converted the control variables of the Boundaries, and control variables of selected footprint variables, to create a set of common control variables. These control variables allow the results of bottom up footprint assessments to the global limits defined by the PBs.

The FB-ESA framework is the only adaptation that considers the interconnectivity of the PBs. They identify that this overlapping of multiple footprint and PBs is a weakness for the FB-ESA. They do not propose a mechanism to deal with this interconnectivity. The authors have applied their framework in a review of 28 countries (Fang et al., 2015b). This study was limited to the assessments of the carbon footprint, water footprint and land footprint of each country.

6.2.6 Connecting the PBs and LCA

Sandin et al. (2015) have proposed life cycle assessment impact (LCA) categories which could be related to the PB control variables. They use this connectivity to propose impact reduction targets at the scale of products.

This is an interesting study as it is the only study with a primary focus on products (as opposed to groups of people). They use a distance-to-target method to translate the limits from the PB variables to the impact category variables. This means they compare the percentage overshoot of impacts to each limit.

Such an approach does not scale sensibly. At a global scale it is reasonable to assume that an 80% overshoot of the PBs for Nitrogen implies that 80% reductions are needed for the LCA impact category "eutrophication" – the impact of nitrogen consumption. This approach can be useful in weighting impact categories in LCA. For example, we can conclude that reducing climate change impacts should generally be prioritised over reducing water use or nitrogen consumption. However, it does not translate into finite targets at different scales. It would not make sense for all sectors to target 80% reductions in eutrophication. Consider two producers of beans. One may use twice as much nitrogen per kg of beans than the other. It is might be quite easy for the producer who is using twice as much nitrogen to reduce their usage by 80%. For the producer who already uses nitrogen sparingly, this reduction may not be feasible. This argument can also be made for very different products and even different sectors.

6.2.7 Comparing the Adaptations of the Planetary Boundaries

Table 5 shows the limits and/or control variables proposed in each adaptation against the PBs. A comparative analysis of each row of this table shows wide variance between the different limits. For example, the PB for climate change has two distinct limits:

1. The concentration of carbon dioxide in the atmosphere should not exceed 350 parts per million (ppm) (parts of atmosphere);
2. The change in radiative forcing (the energy balance at Earth's surface) should not exceed ±1 W/m^2.

Both of these PB limits have been exceeded. To return to 350 ppm would require a negative CO_2 budget. Yet in the adaptations, all the CO_2 budgets are positive – following any of these would lead to further overshoot of the PB for CO_2 concentration. Moreover, they vary widely in both their magnitude and their inclusions. Some include all greenhouse gases. Others are limited to CO_2. Additionally, none of the adaptations address the PB limit for radiative forcing.

Another example of high variability is the adaptations for biosphere integrity. The PB for biosphere integrity is a global extinction rate of no more than 10 extinct species, per million species per year (E/MSY). The control variables in each adaptation are shown in Table 6.

Biosphere integrity is one of the PBs that has already been exceeded. It is thus one of the most critical limits. However, each of the control variables used in the adaptations is different, so it is difficult to assess whether these are equivalent to the PB or not. Several of the PBs are excluded from some or all of the national or regional adaptations, for example, the PB for Atmospheric Aerosol Density – *aerosol optical depth.*

Table 5: Planetary Boundaries downscaled for use at sub-global levels

Earth System Process (Rockström et al., 2009d)	Planetary Boundary Threshold	Adapted Boundary for Sweden (per capita) (Nykvist et al., 2013)	Adapted Boundary for Switzerland (global limits) (Dao et al., 2015)	Adapted Boundary for South Africa (national limits) (Cole et al., 2014)	Adapted Boundary based on the F-B-ESA framework (per capita) (Fang et al., 2015b)	Corresponding LCA Impact Category (Sandin et al., 2015)
Climate Change	Atmospheric CO_2 Change in radiative forcing	CO_2 Emissions: 2 tCO_2/capita/y NA	CO_2 Emissions: 12.3 $GtCO_2$eq NA	CO_2 emissions 451$MtCO_2$ NA	Carbon Footprint 3.1tCO_2-eq/y NA	Climate Change NA
Biodiversity loss	10 species/million species extinct per year	*No boundary set, however 3 alternative indicators identified: (Number of species threatened within the national territory, Number of species threatened globally, Percentage of marine and terrestrial areas protected)*	Biodiversity Damage Potential: 0.16	Endangered and critically endangered ecosystems: 0%	NA	Land occupation, land transformation, biodiversity loss
Nitrogen and Phosphorus Cycle	N_2 removed from the atmosphere P flowing into oceans	Nitrogen Emissions 5kg/capita/y *No boundary set, however alternative indicator identified (Phosphorous fertiliser consumption)*	Nitrogen Emissions: 47.6Tg Phosophorous fertiliser consumption: 38.5 Tg (global limit)	Nitrogen application rate for maize production: 144kgN/ha Total phosphorous concentration in dams 0.1 mg/L	NA	Eutrophication: marine eutrophication, terrestrial eutrophication, terrestrial acidification, eutrophication: freshwater eutrophication
Stratospheric Ozone Depletion	Concentration of ozone	*No boundary set, however alternative indicator identified (Ozone Depleting Potential)*	Not considered as currently phased out	Annual HCFC consumption 369.7ODPt	NA	NA
Ocean Acidification	Mean saturation state of aragonite 2.75	Not assessed as ocean acidification is an impact of climate change	$C0_2$ Emissions: $GtCO_2$ 7.6$GtCO_2$	Replaced by marine harvesting	NA	NA
Fresh Water Use	Freshwater consumption 4,000km^3/year	Water consumption: 585 m^3/capita/y	Not included as considered to be a regional issue	Consumption of available freshwater resources 14,196 Mm^3/y	Water footprint: 40% of the total renewable water resources for that country	Freshwater consumption
Change in Land Use	Land cover converted to cropland 15%	0.3 ha / capita	Surface of anthropised land: 19,362,000 km^2	Rain-fed arable land converted to cropland 12.1%	Land footprint – biocapacity	Land transformation
Chemical Pollution	NA	*No boundary set, however 5 alternative indicators identified (Pesticide regulation, Persistent Organic Pollutants in breastmilk, Methylmercury-based indicator, Embedded use of chemical substances in traded products, Use of the Strategic Approach to International Chemicals Management*	Rationales lacking in setting limit	Not given due to lack of detailed and accurate data	NA	NA
Atmospheric Aerosol Loading	Aerosol Optical Depth	*No boundary set, no indicator proposed*	*Rationales lacking in setting limit*	*Replaced by air pollution*	NA	NA

Table 6: A summary of the control variables used to assess Biodiversity Loss in different adaptations of the Planetary Boundaries

Adaptation	Control Variable proposed for Biodiversity Loss
Sweden	None set but three potential control variables identified: • Number of species threatened within the national territory • Number of species threatened globally • Percentage of marine and terrestrial areas protected
Switzerland	Biodiversity Damage Potential – an estimation of species richness compared to background levels
South Africa	Endangered and critically endangered ecosystems: 0%
FB-ESA	None proposed
LCA-PB	• Land occupation • Land transformation • Biodiversity loss

None of the adaptations can easily be scaled for use across different sectors and scales. The indicators for biosphere integrity are an example of why not. How would any of the indicators be useful to assess the impacts of an individual, a product, or a service? The Biodiversity Damage Potential could not be attributed to any level below global. The LCA indicators of land occupation and land transformation could be used but the third indicator – biodiversity loss – would again be difficult to attribute to a specific activity or set of activities.

The two adaptations of the PBs that linked these to environmental impact assessment mechanisms were developed to enable the comparison of the impacts of activities to global limits. Yet, both have severe limitations. The F-B-ESA framework only proposes footprints and limits for three PBs, with limits for carbon, water, and land footprints (Fang et al., 2015a). Even these three footprints are limited in their scalability. For example, the authors propose a water footprint of 40% of the total renewable water resources for that country. It may be possible to apply a similar approach to a sub-national level. However it is not immediately scalable to other levels. The biogeochemical flow indicator proposed for the LCA adaptation is eutrophication (Sandin et al., 2015). In some instances, this may be attributable to a single source. In many cases, it would not be. It is not an indicator that makes sense to link to human activity at different scales.

It could be argued that in a poly-scalar order it does not matter whether the indicators and exact limits are the same or not as long as they all target roughly the same goal. However, as discussed in Chapter 3, one of the most important elements for effective bottom-up efforts is a sense of trust that others are making the same effort. With such variation between indicators and limits it would be difficult to generate any trust between different stakeholders at an individual, city, national, or business level.

The definition for a poly-scalar approach in Chapter 3 one which is integrative across different scales, sectors, and timeframes, that is not controlled by a single body, but which could be implemented through governance, privatisation, or self-organised management, that is coordinated by a general system of rules which have different mechanisms at different centres of activity. It is apparent from the past adaptations of the PBs that they are not suitable to be the general system of rules for such an approach. The adaptations of the PBs thus far are not consistent with the PBs, or with one another. Further, the level of work that has gone into each of the adaptations is extremely 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.

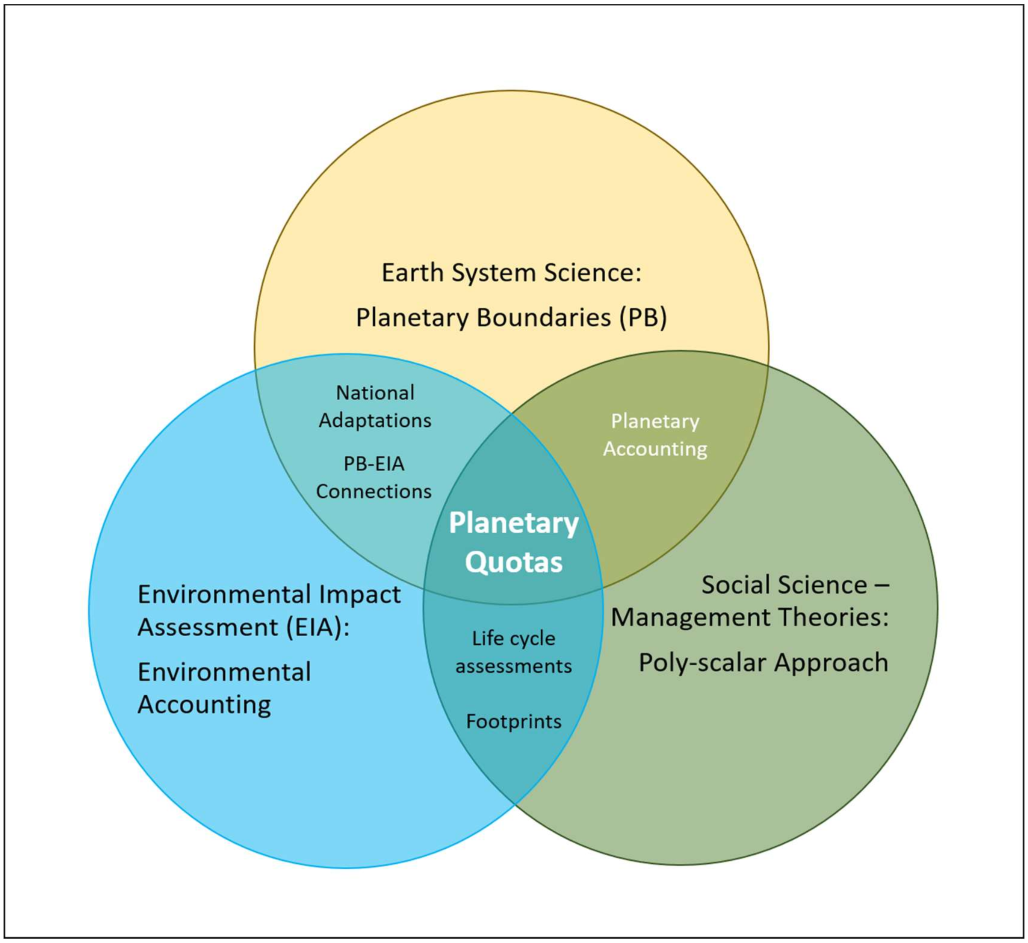

Figure 15: Previous works connect Environmental Accounting with either Management Theories or Earth System Science. The Planetary Quotas connect all three.

Figure 15 shows how environmental accounting methods and the adaptations of the PBs fit into the diagram initially depicted in Figure 14. Each of the adaptations connects the PBs to environmental impact assessment mechanisms. Environmental impact assessments – footprint analyses and life-cycle-assessments – can generally be completed for any scale of activity, i.e. they are poly-scalar in their approach. However, until now, no mechanism had been proposed to bring all three fields together.

6.3 Why the Planetary Boundaries are Difficult to Scale

The global uptake of environmental impact assessments and environmental accounting led to the development of increasing numbers of environmental indicators with which to measure impacts on the environment. Selecting appropriate indicators for different assessments became a major topic of research in itself e.g. (Nolte et al., 2013, Dafforn et al., 2012, Chevalier et al., 2011).

In response to this vast number of indicators, a system to categorise these was adopted by the European Environment Agency – the Driver-Pressure-State-Impact-Response (DPSIR) framework, detailed in Figure 16 (EEA, 2005, Dao et al., 2015, Nykvist et al., 2013). The DPSIR framework not only enables the classification and therefore better understanding of indicators.

- *Driver* indicators describe human needs e.g., kilowatt hours of electricity, kilometres travelled, or litres of fuel for transport;
- *Pressure* indicators describe flows to the environment e.g., CO_2 emissions;
- *State* indicators describe the environment. e.g., the concentration of CO_2 in the atmosphere.
- *Impact* indicators describe the results of changing environmental States e.g., change in average global temperature.
- *Response* indicators describe human responses to the environment which can target any other level of indicator e.g., the Paris Agreement.

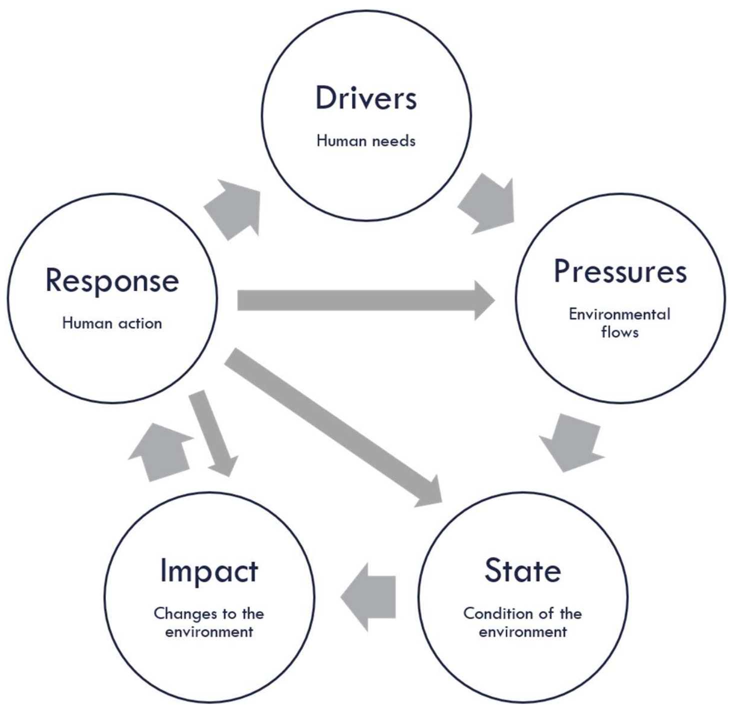

Figure 16: The Driver-Pressure-State-Impact-Response is a framework that can be used to categorise environmental indicators.

To understand why the PBs are so difficult to scale or to connect to existing environmental impact assessment frameworks, it is helpful to consider the DPSIR category of each PB indicator (see Table 7). There are 3 *Pressure* indicators, 5 *State* indicators, and 1 *Impact* indicator.

States and *Impacts* are important indicators as they communicate the status quo. However, human activity cannot easily be compared to *States* or *Impacts*. This is because human activity directly influences *Drivers* and *Pressures*, but only indirectly influences *States* and *Impacts*. *States* and *Impacts* are also inherently difficult to scale. It should be noted that while most Pressure indicators can be easily related to human activity, some cannot (see Box 1).

Table 7: The Planetary Boundaries in the DPSIR framework

Earth system process	Indicator	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

Take one of the PB indicators for climate change as an example – the concentration of CO_2 in the atmosphere – a *State* indicator. There is no straightforward way to divide the responsibility of the state of the atmosphere between different nations, cities, regions, or individuals. Nor can one compare specific human activities to this unit of measure. Imagine 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.

> Box 6.1 – Different Pressure Indicators
>
> Not all Pressure Indicators can be directly related to human activity. Some of the PBs are already *Pressures*, for example, freshwater use. It is straight forward to determine the amount of freshwater used for a given activity, and then to compare this to the global limit for freshwater use. Other *Pressure* indicators cannot be so easily compared to human activity. For example, the PB for phosphorous is the amount of phosphorous flowing into the oceans. Humans mine phosphorous for a number of uses, the main being fertilisers. The pathway of phosphorous from the application of fertiliser to a downstream flow of phosphorous into the oceans is complex. There are many human and natural factors which influence how much phosphorous travels to the ocean, how quickly, and in which ways. It would be difficult to relate this indicator directly to human activity, even though it is a Pressure indicator.

Seven of the ten control variables for the Planetary Boundaries are either States or Impacts. In this way, one can begin to see why applying or scaling the Boundaries is difficult.

6.4 Conclusions - A Need for New Global Limits

This section has shown that there is a need to manage human impacts on the Earth System such that we can remain within the Planetary Boundaries, and the most effective way to do this is using a poly-scalar approach and combining environmental accounting with global (absolute) limits. However, the PBs were not designed to be scaled. Past adaptations have highlighted several limitations in applying the PBs to different scales or connecting these to environmental accounting mechanisms.

What is needed is a new set of global limits that are communicated in terms of Pressure indicators that can be directly compared to any scale or type of human activity, the Planetary

Quotas. Such limits would enable a new type of environmental accounting where impacts can be compared to scientific, absolute limits – Planetary Accounting.

These concepts are the basis of this research project and will thus be further explained in the pursuing sections.

SECTION 2

CHAPTER 7

Translating the Planetary Boundaries into Planetary Quotas

Abstract

There is a need to connect scalable environmental accounting practices with scientific, absolute, environmental limits in a way which enables a poly-scalar approach to managing the Earth system.

The Planetary Boundaries (PBs) are global limits that define a “safe operating space” for humanity. They communicate absolute limits at a global scale. However, they were not designed to be used at any other scale. Many of the limits pertain to control variables which describe the state of Earth-system processes – for example the concentration of CO_2 in the atmosphere – or to global scale environmental impacts, such as the rate of species extinctions per year. Indicators which describe states or impacts are typically not divisible or scalable. It is also difficult to link human activity directly to such indicators. As such it is complicated to determine shares of the safe operating space for different actors or groups such as nations, individuals, or organisations. Moreover, it is difficult to use these indicators to understand the environmental implications of different decisions.

Planetary Accounting is a term I have introduced to describe the process of comparing environmental impacts to scientific global limits. This would allow meaningful decisions to be made at various scales on regulating activities, urban planning, design and technology, policy, industry, and all levels of government legislation.

For Planetary Accounting to work, a new set of absolute limits is needed, to enable policy and action for change at every level. The new limits will need to use control variables which are divisible and can be easily related to human activity at any scale – Planetary Quotas. The Driver-Pressure-State-Impact-Response framework is used here as the underpinning for a framework for the translation of the Planetary Boundaries into Planetary Quotas.

The Planetary Quotas complement rather than replace the Planetary Boundaries. The Planetary Boundaries define a healthy state of the planet. They provide a gauge of the magnitude and urgency of the situation. They are not a guide to resolving planetary health. In contrast, the Planetary Quotas are the prescription for a healthy planet. If humanity live within the Planetary Quotas, we will be able to return to and remain within the Planetary Boundaries.

The Planetary Quotas form the basis of Planetary Accounting which will enable the practical application and communication of how to live within the Planetary Boundaries at different scales of human activity.

7.1 Introduction

There is a need to measure human impacts at any scale against absolute, environmental, global limits, as explained in Section 1. There are existing limits – the Planetary Boundaries (PBs) – which define absolute, environmental limits that would allow the Earth System to continue to operate in a state that is hospitable to humanity. These limits cannot easily be used at different scales or applied to human activity. Herein lies the need for this research.

Planetary accounting is the process of comparing the environmental impacts of human activity to global limits. For this to work, new limits are needed that can be compared to human activity at any scale – Planetary Quotas (PQs).

The purpose of Section 2 is to present the overall methodology and detailed methods used to develop a high-level Planetary Accounting Framework (PAF) and the PQs. The chapter begins with an overview of the concepts of planetary accounting and the PQs. This is followed by a more detailed discussion of the Driver-Pressure-State-Impact-Response framework, first presented in Chapter 5, which forms the underpinning of the methods presented later in this chapter. I introduce methodologies which have been specifically developed for multi-disciplinary projects, and present the methodology used for this project. Finally, I present the overall methods used to translate the PBs into PQs.

The detailed methods used to derive each of the Quotas differ. For clarity, these methods are presented within the results section in the corresponding PQ chapters.

7.1.1 Planetary Quotas

The PBs communicate important information about the state of the global environment and the risk that human activity will fundamentally change this. For example, the PBs tell us that the concentration of CO_2 in the atmosphere is too high; that the current rate of species loss is dangerous, and that the acidity of the oceans is putting the Earth System at risk. The Planetary Boundaries can be likened to a planetary health check. If a person visits the doctor, she might measure his blood pressure, heart rate, weight, and liver and heart function. By comparing these results to healthy limits, she can tell me whether he is in good health or not, and, if not, which areas of his health need the most focus. These health checks are important. They can give an early indication that there are warning signs for major health problems. Is the patient likely to experience liver failure? Is he at risk of a heart attack? However, on their own, these indicators of the *state* of the patient's health do not help the patient to determine how to become healthy.

In contrast, the Planetary Quotas communicate how to achieve planetary health. They are annual budgets for human impacts on the planet. The PQs are the prescription for a healthy Earth. In the example of an unhealthy patient, the doctor is likely to tell the patient what he should do to return to good health. She might prescribe a minimum level of exercise and a maximum calorific intake. She may even suggest that some behaviours are unacceptable – for example, she is likely to say that no amount of smoking is safe. The PQs tell us how to live within the PBs, for example, limits for emissions of CO_2 to the atmosphere, minimum reforestation rates, and maximum land occupation.

In the same way that an overweight patient who begins a diet will not immediately return to good health, the PQs will not immediately return the Earth System processes to within the PBs. However, with time, the health of the patient and the planet will gradually improve and eventually return to the recommended levels.

The PQs also help us to understand the direction of travel with respect to the safe operating space of the PBs. For example, the health of a healthy patient with very unhealthy habits is likely to deteriorate. We are currently operating within the limits of some of the PBs. However, if we exceed the corresponding PQs each year then we can predict with reasonable confidence that over time we will exceed those PBs.

7.1.1.1 Interconnectivity

The Planetary Boundaries have a high level of interconnectivity. Exceeding one PB affects our ability to remain within others. For example, the control variable for biosphere integrity is extinction rate – the number of extinct species per million species per year (E/MSY). There are five key drivers for species extinction (Galli et al., 2014, Rockström et al., 2009a, Cucek et al., 2012, Secretariat of the CBD, 2014, MEA, 2005):

1. Climate change
2. Habitat loss
3. Pollution
4. Over-exploitation
5. Invasive species

Of these drivers, three are other PBs, or at least closely related to PBs. Climate change is the obvious example. This means that to operate within the PB for biosphere integrity, it is likely that the PBs for climate change will also need to be respected. Habitat loss is not a PB in and of itself but there is a PB for land-use is which is closely related. Pollution is considered across several PBs: air pollution is addressed in the PB for atmospheric aerosol density; water pollution – is addressed to some extent via the PBs for nitrogen and phosphorous.

For the PQs to be a robust prescription for a healthy planet, the interconnectivity between the PBs needs to be carried over to the PQs. There are nine PQs and nine PBs – but this is coincidental. There is not a linear relationship between the two sets of limits. Again, the example of health can be used to describe this relationship. If a person is overweight, this influences other elements of his health. His weight, blood pressure, heart rate, and liver function are not separate and independent of one another, they are all interconnected. When his doctor prescribes a diet, or exercise, she is not just targeting weight reduction. She is also aiming to improve his blood pressure, heart function, and other elements of his health. The relationship of the PQs and PBs is similar. Almost all of the PQs are linked to more than one of the PBs. Some PBs are linked to almost every PQ, for example the PB for biosphere integrity is linked to all nine PQs.

7.1.2 The Planetary Accounting Framework

Chapter 3 showed that carbon accounting is different to most environmental accounting practices because the results can be put into the context of global, scientific limits. Planetary accounting builds on this idea. It describes the practice of comparing environmental impacts of human activity to global limits.

The Planetary Accounting Framework (PAF) proposed in this thesis provides an overview of how the Planetary Quotas can be used to quantify limits for environmental impacts from different levels of activity that correspond to operations the are within a fair share of the Planetary Boundaries. However, it is my intention that the term *planetary accounting* could be used to describe any environmental accounting against global scientific limits. Carbon accounting is, thus, one type of planetary accounting.

Chapter 3 argued that the best way to manage the Earth System is through a poly-scalar approach coordinated by a general system of rules. The PAF shows how this general system of rules could work across different scales using the PBs as the scientific basis. In future, the PBs may be updated or replaced by more accurate or relevant global limits. Even now, there are global limits which have been proposed that which are not included in the PB framework – for example maximum material consumption proposed by (Hinterberger and Schmidt-Bleek, 1999).

The concept of planetary accounting should therefore not be limited to the framework presented here. It is not a static process of accounting against predetermined limits that do not change. It is a dynamic process, of comparing environmental flows due to human activity to global limits as they are understood at the time of assessment. It is important for policy and business decision making that planetary accounting can be treated in a static way – where policies and decisions are made on the basis of fixed limits. However, it will also be important that these limits are reviewed and updated over time. Carbon accounting gives an example of how this can work. Previous policies and decisions have been developed on the basis of a 2℃ warming limit. The science now shows that a target of 1.5℃ would be safer so policies and decisions are being updated accordingly. This does not negate the importance of the efforts that were aimed at 2℃ of warming. Further, carbon accounting is not always done in accordance with the greenhouse gas protocols which define formal procedures for carbon accounting e.g., (Greenhalgh et al., 2005). For some applications, this level of rigour is unnecessary. The PAF is a high level framework that shows how planetary accounting can work using the Planetary Quotas as global limits. It is a mechanism that brings together environmental accounting practices, current global limits, and the latest behaviour theories of poly-scalar management. More detailed frameworks will be needed to provide the detail of how different types of planetary accounts should be undertaken.

Nonetheless, the PAF shows how global limits to be scaled down to determine an individual, city, company, or national share of the safe operating space. The PQs define the key "environmental currencies" to be assessed, such as the mass of carbon emitted, the volume of water consumed, and the area of land appropriated for the activity. A company or city might find themselves in deficit in some currencies and in credit in others.

There are many opportunities for implementations of the PAF. Individuals could compete with friends and strangers across the globe to live within their share of the planet's limits through a smart phone app. 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. Environmental impact trading could happen in multiple environmental currencies at any scale – from individual to national. The real costs of exceeding global limits could be used to assign a monetary value to each environmental currency, allowing the incorporation of environmental costs into our economic framework. A product labelling system could be developed to disclose "Planetary Facts", of products – disclosing key environmental impacts of the product – in the same way as nutritional fact labels disclose key nutritional information.

In short, a consistent, robust, and scientifically sound way of measuring human activity against global, absolute limits would enable a wide range of different implementations that could help humanity to manage the Earth System.

7.2 Methodologies for Multidisciplinary Research

There is no singular field of science that encompasses the research presented in this thesis. The Planetary Quotas and Planetary Accounting Framework are solutions derived from scientific investigation across the broad fields of science, governance, and community. There are very few methodological frameworks for research that deals with the intersection between these fields (Brandt et al., 2013, Stocker and Burke, 2017). Multi-disciplinary research design is often based on a combination of different methodologies from the relevant disciplines.

Traditionally, scientific investigation was assumed to have a high degree of certainty and to be free of value judgements. Due to the urgency of environmental problems facing society today, this is changing. Science with limited certainty needs to be used to make decisions as to how best to manage the environment. Funtowicz and Ravetz (1993) introduced a new concept to describe this new type of research – *post-normal science*. They define post-normal science as the approach needed when decision stakes are high, systems uncertain and decisions urgent.

In an editorial on post-normal science, Ravetz (1999) describes the commonalities for such an approach to using science to inform governance. These include being critical and reflexive, aware of uncertainties, the inclusion of normative perspectives, and having a strong focus on quality.

The underlying premise of post-normal science is that in the presence of uncertain systems, values held by the agent will influence the outcomes. Ravetz (1999) argues that this is both natural and legitimate. He makes the case that a degree of value judgement is present in all research (e.g., in balancing selectivity and sensitivity or through the decisions for manging outlier data). Value judgements in themselves do not reduce the validity of research. They are only a problem when they are not made transparent, and where adequate quality-control methods are not employed.

Traditional scientific approaches use peer review as a quality-control method. In a post-normal science approach, the common quality-control method is to use "extended peer-communities". Extended peer-communities have been used for some time to guide the development of projects and policies, even if the term has not been used. For example, when implementing new infrastructure that will affect many players, governments may invite community feedback to understand any problems and/or opportunities that they may not otherwise have understood.

The common element of extended peer-community reviews is that the participants are invited to review a proposal based on science, and that their feedback is used to improve the quality of the final solution. The process generally follows that a period of scientific investigation is undertaken to develop a preliminary solution. This is followed by engagement with the extended peer community. The feedback gathered from the investigation is then used to refine the solution.

Integrative research is another multidisciplinary approach developed in 1986 (Douglas, 2005). Douglas defines this approach as a process of integrating "intuition, reason and imagination" to address a complex problem. The underlying premise of integrative research is that opposing views or models should not be assessed to determine which is better. Rather, they should be assessed, analysed, and considered, with a view to developing a new approach that takes the best aspects from both models. Integrative research uses a systemic approach – considering the problem and solution as a whole, rather than assessing and resolving the problem in parts.

7.2.1 Methodology for the Development of the Planetary Quotas and Planetary Accounting Framework

The methodological approach I applied to my research design combines the post-normal science approach and the integrative approach. The Planetary Quotas are a set of scientific numbers, whereas the Planetary Accounting Framework is a theoretical guideline. However, my methodology applies to these two components of my research as a whole, not as two parts.

The research project can be divided into several stages:

1. Preliminary model development
2. Preliminary dialogue with extended peer community
3. Model refinement
4. In-depth dialogue with extended peer community
5. Model completion

All stages of this work were undertaken using an integrative approach. For example, in the first stage, I included a thorough investigation of different types of environmental accounting. This allowed me to gain the insights needed to develop the concept of planetary accounting. In the second stage of the project I took insights from feedback regarding specific aspects of the project – such as concerns over regional availability of water – and applied this thinking across the entirety of the model.

7.2.1.1 Dialogue with an extended peer community

I took an organic, rather than a formal approach to my engagement with the extended peer-community. In the first period of engagement I presented my work to colleagues and friends in formal presentations, and during informal catch ups. I began each dialogue by announcing that I was seeking feedback – but I did not frame this request further by suggesting what type of feedback I was looking for. This was intentional. The purpose of the engagement was to understand how the model might be received when finally released to the general public. The outcome was very effective. The dialogue ranged from specific concerns over particular Quotas, to high level discussions over the ethics of such a concept.

The second period of engagement was slightly more structured. The scientific investigation required for the project was very broad, so I was seeking not only feedback regarding the model as a whole, but also a depth of understanding and review that could only be gained through engagement and dialogue with experts across the relevant fields (explained further in Box 7.2). I contacted the authors of the primary research used for each Quota, as well as the authors of the Planetary Boundaries and set up meetings with all who responded. In addition to these meetings, I submitted abstracts for all the major conferences I could find on the topics of the Planetary Boundaries, social sciences and sustainability, and Earth System sciences that took place during this second period of extended peer community-engagement.

The outcomes of the dialogue during both stages of engagement are discussed later in this chapter following the detailed methods used in the preliminary design of the model.

7.3 Methods

The European Union's Driver-Pressure-State-Impact-Response (DPSIR) framework was introduced in Chapter 5. To recap, this is a framework that can be used to categorise environmental indicators. All environmental indicators are either Drivers (human needs), Pressures (environmental flows), States (describing the state of the environment) or Impacts (describing changes to the environment). Most Pressure and Driver indicators can be easily related to human activity (though not all) and applied across different scales. In contrast, it is difficult to scale State or Impact indicators or to compare these directly to human activity.

As discussed in Chapter 5, the DPSIR framework can be used to explain why the Planetary Boundaries cannot be easily compared to human activity at different scale. Seven of the ten control variables in the PB framework are either State or Impact indicators. The DPSIR framework is not only useful to understand the limitations of the PBs. It is can also be used to translate Impacts and States into corresponding Pressures.

There is a causal relationship between the categories of the DPSIR framework as follows: *Human needs (Drivers) lead to environmental flows (Pressures) which determine the State. Changing the State of the environment can lead to environmental Impacts.* As an example, a human need might be for heating, measured in kilowatts of energy (the Driver). Creating this energy leads to an environmental flow of carbon dioxide to the atmosphere (the Pressure). The amount of carbon dioxide released determines the concentration of carbon dioxide in the atmosphere (the State). If the concentration of carbon dioxide in the atmosphere changes, this leads to climate change (the Impact).

In this way, the Planetary Boundaries can be translated into Pressures, and then these Pressures can be used to derive Planetary Quotas. Using Pressure indicators for the Planetary Quotas means that these global limits can be divided, allocated, or shared in various ways amongst individuals or groups of individuals (e.g. communities, cities or nations). They can also be shared amongst different sectors and/or allocated to any scale of organisation. This approach was used in two of the adaptations of the PBs to determine national targets for Sweden and Switzerland (Dao et al., 2015, Nykvist et al., 2013). However, neither study

Box 7.1: Why use Pressures not Drivers?

Both Driver and Pressure indicators can be directly applied to human activity. It is common practice, for example, to measure the carbon emissions (a Pressure) for a given activity or to monitor electricity consumption (a Driver).

The decision to use Pressure indicators rather than Driver indicators was for simplicity – using the example of atmospheric CO_2, there is only one environmental flow (Pressure) that effects this – the emission (or uptake) of CO_2 to (from) the atmosphere. In contrast, there are many human drivers (needs) which lead to the emission of CO_2. At a high level these would include, a need for transport, for electricity, for concrete, and for deforestation for agriculture. However, each of these Drivers can be traced back to underlying drivers – for example the need for transport is due to the need to get to work, the need to socialise, etc.

applied this approach across all of the PBs (see Chapter 5). It would also be possible to do this for Drivers (see Box 1).

Building on the approaches used by Dao et al. (2015) and Nykvist et al. (2013) in their adaptations of the Planetary Boundaries, the methodology used for the adaptation of the Boundaries to alternate control variables is as follows:

1. Determine a full list of critical pressures by:
    a) Disaggregating 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 scaleable pressure indicators which can be easily related to human activity which correspond with one or more critical pressures by:
    a) Assessing whether indicators are equivalent with resepect to the corresponding PBs (i.e. whether reductions in one pressure could offset increases in another) and if so determine whether existing indicators could be used for more than one pressure.
    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.
6. Engage with experts in relevent field to gain feedback on both the concept of the PQs and the specific PQs and use their insights to refine the PQs.

Stages 1 – 4 and Stage 6 of the methods described above apply to the PBs and PQs as a whole. These stages are discussed in more detail in the following sections. The specifics of Stages 3 and 4, and Stage 5 are discussed in detail for each PQ in the following chapters.

7.3.1 Critical Pressures

There are one or more pressures from human activity effecting each of the PB limits[14]. Some of these pressures have a major impact on the PBs, others have a relatively minor impact. Accounting for all the pressures for every PB is an onerous task. To simplify life-cycle assessments, there is typically a policy to exclude any activities with less than a 1% impact on the final results, provided the total exclusions do not exceed 5%. To simplify the translation of PBs to PQs, a similar approach was taken. Any pressure contributing less than 1% to the corresponding PB was excluded to a maximum of 5% exclusions for any given PB. For the purpose of this project the remaining pressures are defined as "critical pressures".

A literature review was completed to determine the critical pressures for each of the PBs (see Table 8).

[14] The term Planetary Boundary is often used to describe the Earth System processes in the PB framework (e.g. climate change), rather than the PB limits (e.g. atmospheric CO_2 concentration or change in radiative forcing). It is important to differentiate between the two definitions here as a list of pressures contributing to climate change is less specific than a list of pressures contributing to atmospheric CO_2 concentration.

Table 8: Anthropogenic pressures corresponding to each Planetary Boundary limit

PB Limit indicator (Earth System process)	Pressures
Concentration of CO_2 in the atmosphere (climate change)	• Carbon dioxide emissions (IPCC, 2013b)

Radiative Forcing (climate change)[1,2,3]	• Emissions of well mixed greenhouse gases (GHGs):
	  ○ Carbon dioxide (CO_2)
	  ○ Methane (CH_4)
	  ○ Nitrous oxide (N_2O)
	  ○ HaloCarbons (HCFCs and CFCs)
	  ○ Hydrofluorocarbons (HFCs)
	  ○ Perfluorinated compounds (PFCs)
	  ○ Sulfur hexafluoride (SF_6)
	• Emissions of short lived GHGs
	  ○ Carbon monoxide (CO)
	  ○ Non methane volatile organic compounds (NMVOCs)
	  ○ Nitrate (NOx)
	• Emissions of aerosols and precursors (detailed under Aerosols)
	• Change in albedo
	  ○ Climate change
	  ○ Land-use change
	(Myhre et al., 2013a, Forster et al., 2007) (Shine et al., 1995)

Saturation state of aragonite (ocean acidification)	• Emissions of carbon dioxide (CO_2) (IPCC, 2014a)
Remaining forestland (land-use change)	• Deforestation • Climate change (IPCC, 2014a)

Concentration of stratospheric ozone (ozone depletion)	• Emissions of ozone depleting substances
	  • Halons
	  • Chlorofluorocarbons (CFCs)
	  • Carbon tetrachloride (CCl_4)
	  • Methyle chloroform ($C_2H_3Cl_3$)
	  • Hydrochlorofluorocarbons (HFCs)
	  • Hydrobromofluorocarbons (HBFCs)
	  • Methyl bromide (CH_3Br)
	  • Bromochloromethane (CH_2BrCl)
	  • Hydrochlorofluorocarbon (HCFCs)
	  • Hydrofluorocarbons (HFCs)
	(UNEP, 2017a)

	• Nitrous Oxide (N_2O) (Portmann et al., 2012)
Aerosol optical depth (atmospheric aerosol loading)	• Emissions of aerosols and precursors: ○ Nitrate (NH_3) ○ Sulphate (SO_2) ○ Primary Organic Aerosols (POA) ○ Black carbon (BC) ○ Organic aerosols (OA) (brown carbon, primary biological aerosol particles (PBAPs)) ○ Nitrogen oxides (NO_x) ○ Non-methane volatile organic compounds (NMVOCs) • Land-use change (resulting in mineral dust) (Boucher et al., 2013)
Water consumption (freshwater use)	• Water consumption (Hoekstra and Mekonnen, 2012)
No indicator proposed (novel entities)	• Use of chemicals[4] • Disposal of chemicals[4]
Intentionally fixated nitrogen (biogeochemical flows)	• Release of reactive nitrogen to the environment (Leach et al., 2012)
Phosphorous flow to oceans (biogeochemical flows)	• Release of phosphorous to the environment (Schröder et al., 2010)
Extinction rate (biosphere integrity)	• Climate Change ○ See pressures for concentration of CO_2 and radiative forcing • Habitat loss ○ Land conversion ○ Land segregation ○ Land degradation ○ Climate change (see above) • Pollution (air, water, land) ○ See pressures for novel entities, aerosol optical depth, nitrogen fixation, and phosphorous flow to the oceans • Introduction of species • Overexploitation of species (MEA, 2005)

Notes:

1. Water vapour is the greenhouse gas with the greatest effect in the atmosphere. It is not included the list of critical pressures because it is not considered to be a forcing

agent. It is often termed a “secondary GHG”. This is because water vapour presence is predominantly determined by air temperature. It is thus a feedback not a pressure (Myhre et al., 2013b).

2. Ozone is a secondary GHG and a secondary aerosol and thus excluded. It is formed by photochemical reactions – reactions from sunlight hitting air with particular molecules. The primary drivers of tropospheric ozone (an aerosol) are emissions of methane, nitrous oxides, carbon monoxide, and non-methane volatile organic compounds. Stratospheric ozone RF is predominantly from ozone depletion by halocarbons. These primary molecules are all included in the list of critical pressures.
3. HFCs, PFCs and $SF_{6,}$ each contribute less than 1% towards total radiative forcing (and therefore collectively less than 5%) (Myhre et al., 2013b). These were the only exclusions from the full list of pressures.
4. The PB for novel entities does not have a proposed indicator. As such, the pressures listed are based on the Earth System process – i.e. the introduction of novel entities.

A review of Table 8 highlights that many of the pressures pertain to more than one PB limit. Table 9 shows the same data consolidated to show each pressure only once against each of the corresponding PB limits.

Table 9: List of critical pressures

Critical Pressures	Corresponding Boundary
Carbon dioxide emissions	Concentration of CO_2 in the atmosphere Radiative forcing Saturation state of aragonite Extinction rate Remaining forestland
Methane emissions	Radiative forcing Extinction Rate
Nitrous oxide emissions	Radiative forcing Extinction Rate Concentration of stratospheric ozone
Deforestation	Radiative forcing Aerosol optical depth Extinction rate Remaining forest
HaloCarbon emissions	Radiative forcing Extinction Rate Concentration of stratospheric ozone
Hydrochlorofluorocarbon	Concentration of stratospheric ozone
Halon emissions	Concentration of stratospheric ozone
Chlorofluorocarbon emissions	Concentration of stratospheric ozone
Carbon tetrachloride emissions	Concentration of stratospheric ozone
Methyle chloroform emissions	Concentration of stratospheric ozone
Hydrochlorofluorocarbon emissions	Concentration of stratospheric ozone
Methyl bromide emissions	Concentration of stratospheric ozone
Bromochloromethane emissions	Concentration of stratospheric ozone
Hydrobromofluorocarbon emissions	Concentration of stratospheric ozone
Hydrofluorocarbon emissions	Concentration of stratospheric ozone
Carbon monoxide emissions	Radiative forcing Aerosol optical depth
Non-methane volatile organic compounds	Radiative forcing Aerosol optical depth
Nitrate emissions	Radiative forcing Aerosol optical depth
Sulphate emissions	Radiative forcing Aerosol optical depth
Black carbon emissions	Radiative forcing Aerosol optical depth
Organic carbon emissions	Radiative forcing Aerosol optical depth
Water consumption	Water consumption

Release of reactive nitrogen to the environment	Intentionally fixated nitrogen
Phosphorous consumption	Phosphorous flow to the ocean
Use of chemicals	(Novel entities)
Disposal of chemicals	(Novel entities) Water consumption
Land conversion	Radiative forcing Aerosol optical depth Extinction rate Remaining forest
Land segregation	Remaining forest Radiative forcing Extinction rate
Land degradation	Remaining forest Radiative forcing Extinction rate
Introduction of species	Extinction Rate
Overexploitation of species	Extinction Rate
Water consumption	Water consumption

7.3.2 Indicator Selection

Table 9 was used to identify equivalent critical pressures – i.e. critical pressures with the same set of corresponding PB limits. The proposed indicators for each critical pressure or set of critical pressures are shown in Table 10. The indicator and limit for each are discussed in the following chapters (as indicated in the table)

Table 10: PQ indicators for each critiral pressure or group of pressures and corresponding PBs

PQ Indicator	Critical Pressures	Corresponding PB
Carbon dioxide emissions (See Chapter 7)	Carbon dioxide emissions	Concentration of CO_2 in the atmosphere Radiative forcing Saturation state of aragonite Extinction rate Remaining forestland
Methane and nitrous oxide (MeNO) emission (See Chapter 8)	Methane emissions Nitrous oxide emissions	Radiative forcing Extinction Rate Aerosol optical depth Concentration of stratospheric ozone[1]
Reforestation (See Chapter 9)	Deforestation	Concentration of CO_2 in the atmosphere Radiative forcing Aerosol optical depth Extinction rate Remaining forest
"Montreal Gas" emissions (See Chapter 10)	HaloCarbon emissions Hydrochlorofluorocarbon Halon emissions Chlorofluorocarbon emissions Carbon tetrachloride emissions Methyl chloroform emissions Hydrochlorofluorocarbon emissions Methyl bromide emissions Bromochloromethane emissions Hydrobromofluorocarbon emissions Hydrofluorocarbon emissions	Concentration of stratospheric ozone Radiative forcing[2] Extinction Rate[2]
Aerosol and precursor emissions (See Chapter 11)	Carbon monoxide emissions Non-methane volatile organic compounds Nitrate emissions Sulphate emissions Black carbon emissions Organic carbon emissions	Radiative forcing Aerosol optical depth Extinction rate

Water use (See Chapter 12)	Water consumption	Water consumption
	Use of chemicals[3]	(Novel entities) Water consumption
	Disposal of chemicals[3]	
Nitrogen released to the environment (See Chapter 13)	Release of reactive nitrogen to the environment	Intentionally fixated nitrogen
Phosphorous use (See Chapter 14)	Phosphorous use	Phosphorous flow to the ocean
Land Use in *percentage disappearing fraction* (of species) (See Chapter 15)	Land conversion	Radiative forcing Aerosol optical depth[4] Extinction rate Remaining forest
	Land segregation	
	Land degradation	
	Introduction of species[5]	Extinction rate
	Overexploitation of species[5]	

Notes:

1. Nitrous oxide emissions contribute to the depletion of the ozone layer while methane does not. See Chapter 8 for a discussion on this.
2. Halocarbons are a greenhouse gas as well as an aerosol precursor. As such, the emission of halocarbons contributes to radiative forcing and extinction rate as well as to the concentration of stratospheric ozone . The PQ for Montreal Gases (which includes halocarbons) is zero emissions. As such, the impacts of halocarbons on radiative forcing and extinction rate can be discounted (see Chapter 10)
3. There is no indicator proposed for the PB for novel entities. As such, it is not possible to list associated pressures. However, many chemicals that are disposed of end up in our waterways. The amount of water needed to assimilate chemicals is often used as a proxy indicator for chemical pollution. This is how the PQs incorporate novel entities (see Chapter 12)
4. Land conversion to desert releases sand and dust particles which affect aerosol optical depth. PQs for deforestation and percentage disappearing fraction of species both indicate a positive shift towards less desert area and more forestland. As such there should be no further net contribution from land conversion to aerosol optical depth.
5. There is no straightforward mechanism to measure pressures associated with the introduction or overexploitation of species. Percentage disappearing species is a land-use based indicator that can be used as a proxy to measure human pressures on biodiversity (see Chapter 15)

7.3.3 Expert Engagement

The second phase of expert engagement took place in Europe between March 8, 2017 and March 2, 2018 (see Box 7.2). During this time, I visited the following institutes:

- The Stockholm Resilience Centre
- The Netherlands Environmental Agency (PBL)
- The Water Department at Twente University
- The Water Footprint Network
- Common Home of Humanity
- The PIK Institute for Climate Change
- University of Coimbra
- Denmark Technical University
- Auckland Council
- Den Hague University

I also contacted aerosol experts at NASA to gain feedback via email as I was unable to visit NASA in person.

During this period, I also attended the following conferences:

- Making the Planetary Boundaries Work – Berlin (delegate)
- Resilience 2017 – Stockholm (speaker and poster presenter)
- World Resources Forum – Geneva (speaker – invited by the World Resources Institute)
- Global Research Forum on Sustainable Production and Consumption – Brighton (speaker)

At each institute and conference, I presented my research and requested feedback. I did not specify the type of feedback I was looking for – I left it as an open question to the audience. During this period, I received feedback from people with a wide range of backgrounds including specialists in water, nitrogen, atmospheric chemistry, and land use, government and business representatives, and the lead authors of the original Planetary Boundaries Framework.

The key themes of the feedback were:

1. Regionality

Feedback consistently returned to concerns over dealing with regionality – in particular with respect to water consumption.

2. Interconnectivity

   The Planetary Boundaries have an extremely high level of interconnectivity and thus each of the Planetary Quotas are strongly interconnected with one another, and with the PBs.

3. Ethics

   There was substantial concern from some groups over the ethics of Planetary Quotas and any form of allocation.

4. Feasibility

   Some were concerned at the distance of some PQs to current global impacts.

The PQs and PAF address this feedback as follows:

1. Regionality

   The PQs are not intended to be a tool to manage local and regional impacts. They are intended as a guideline to allow the impacts of action at every scale of activity to be understood in terms of critical global limits. Critical global limits are defined by the Planetary Boundaries as limits to Earth System processes beyond which the departure from a Holocene-like state is high. This does not mean that living within the PBs (or within the PQs) will address all environmental issues. There will still need to be local awareness and action for local environmental problems. The question of regionality and water is answered in depth in Chapter 12.

2. Interconnectivity

   The interconnectivity of the PBs and PQs is considered in the methodology to an extent. Rather than translating one PB to one PQ, the PBs are collectively translated into a set of Pressures and these Pressures are then translated into the PQs. Many of the PQs must therefore respect multiple PBs – in this instance the most stringent limit for the PQ is selected. There is deeper interconnectivity that is not addressed. For example, as more nitrogen fertiliser is applied to plants, the uptake of carbon dioxide by these plants is higher. This interconnectivity pertains more to the methods for calculating impacts and should be considered in any future development of impact assessment methods and/or the development of impact calculators.

5. Ethics

   The Planetary Accounting Framework includes a mechanism through which different methods of allocation can be used to determine a “fair share” of the Planetary

Quotas for any scale of activity. It is not intended that the PQs will be or should be imposed on the global population in a top down manner. The intention is quite the opposite. The purpose of the PQs and PAF is that they are flexible enough to be used in many different ways by different users.

6. Feasibility

   It will be extremely challenging to make the level of change needed to operate within some of the PQs. The purpose of the PQs is not to determine a maximum level of feasible change. Rather, it is to determine the minimum level of necessary change. It may not seem initially feasible to operate within these limits. The alternative is that we risk changing the Earth System to a different, and potentially uninhabitable state for humanity.

Box 7.2: The European Research Trip

To complete the extended community engagement required that I spend a substantial portion of the last year of my research in Europe as this is where the majority of global experts in the field are based. I therefore packed my two pre-schoolers and husband into a caravan and the four of us travelled from one institute to another across Europe. Between visits to research centres, my office changed daily – from beachside cafes where I could see the kids and my husband building sandcastles, to busy street side cafes in Portugal, to the corner of the caravan where no suitable alternative was available.

There were some unexpected events along the way. The car broke down at least a dozen times. There were several injuries (including the dislocation of both of my knees in a single fall which gave me my first ride in an ambulance and left me in two full leg braces for the last month in Europe). The climax was the discovery that our beloved caravan had been stolen 10 years ago. The Stuttgart police relieved us of our home with 30 minutes notice, leaving us stranded with a handful of quickly gathered essentials, a broken-down car, two leg braces, and no accommodation at sunset.

Despite the hiccups, the research trip was an incredible journey for me professionally. I met so many inspiring experts across the different fields of my research project and built relationships that will last for many years to come. It was also a remarkable experience for both me and my family on a personal level. We gained a huge amount from the trip and are closer as a family unit because of it. My 2-year-old daughter can still remember words in at least 5 languages 6 months after leaving Europe. My son, who is 4, is still struggling to come to terms with why the view from the window of our house stays the same every day. My husband and I talk wistfully of the caravan year and are already making plans to for another, similar sabbatical in future.

7.4 From PBs to PQs

The path from PBs to critical pressures to PQs is shown in Figure 17. The Earth System – the fundamental core for both the Planetary Boundaries and Planetary Quotas, is shown in the centre. Each of the PB limits are shown in blue boxes. Altering any of the Earth System processes could change the Earth System.

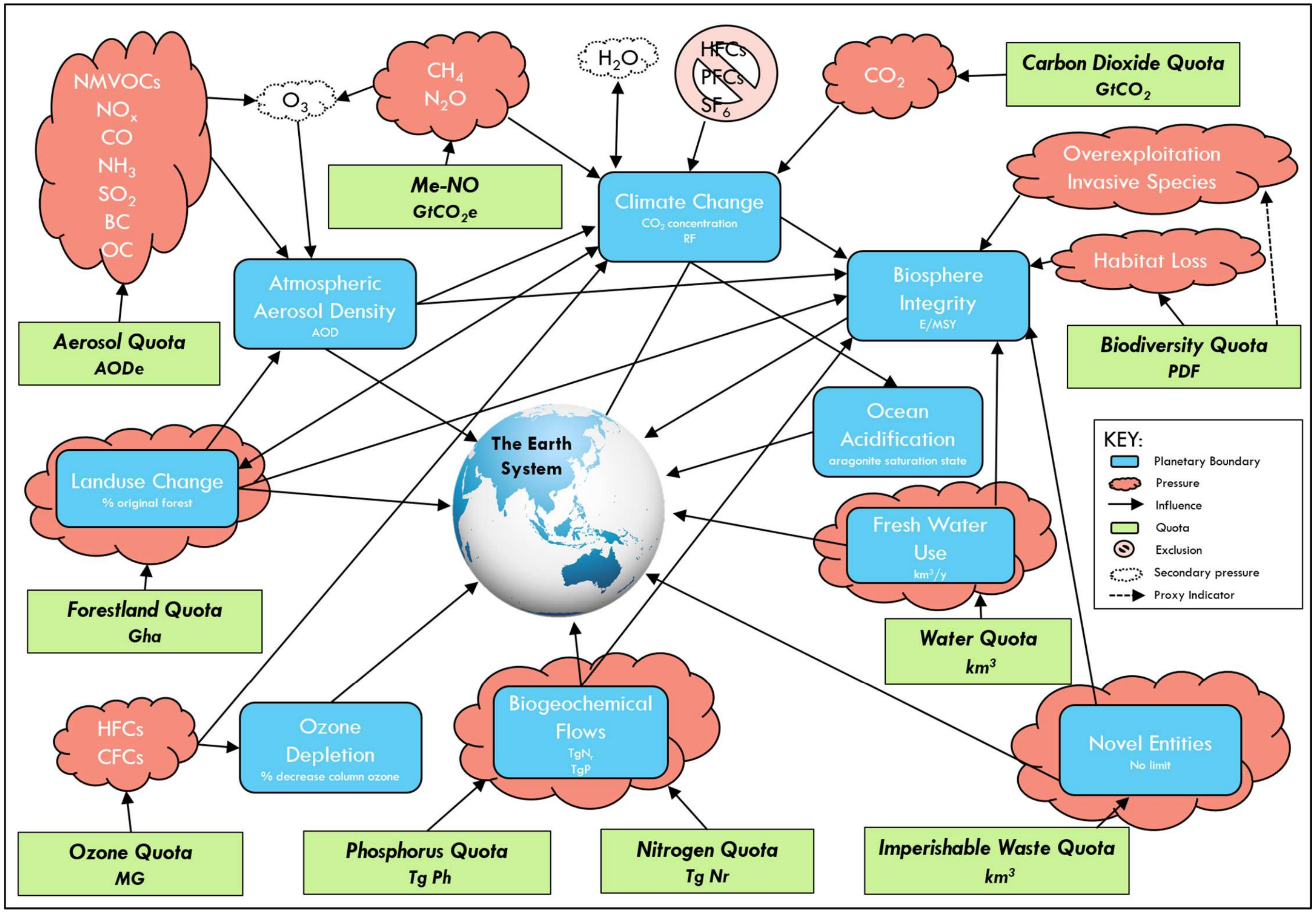

Figure 17: The Planetary Boundaries define key processes which influence the Earth System. These are distilled into Pressures through the UN DPSIR framework. Critical pressures are shown in orange bubbles – grouped for equivalence with respect to the PBs. Excluded pressures are shown in a pale orange crossed out circle. Secondary pressures are shown in white. PQs for each set of pressures are shown in green boxes. Causal relationships are shown with arrows.

The purpose of Figure 17 is to show the high level of interconnectivity between the two systems. To understand the influence of any one of the PQs one can follow the path(s) indicated by the arrows from the PQ to the Earth System at the centre. Each PB passed is affected by the upstream PQ.

Figure 18 shows the direct relationship between the PBs and each PQ, without the critical pressures. This figure further highlights the interconnectedness of all the Boundaries, in particular that of the two "core Boundaries" identified as such in the 2015 update of the PBs – climate change and biosphere integrity (Steffen et al., 2015).

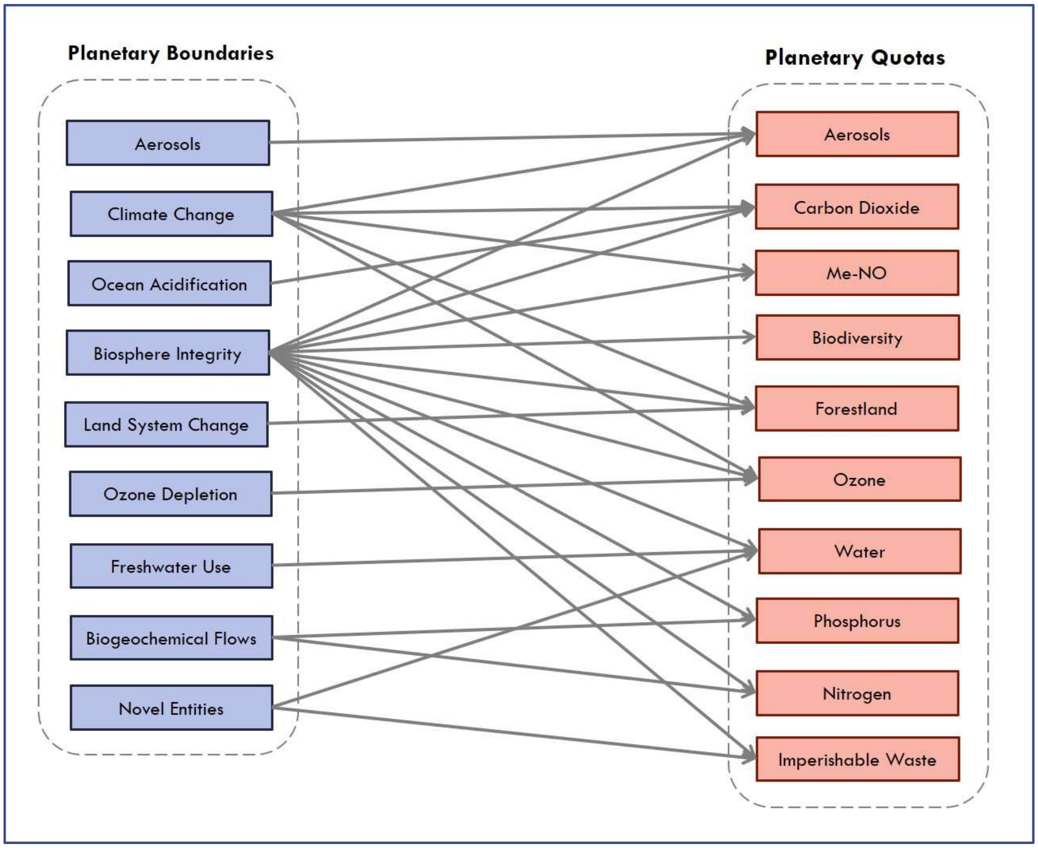

Figure 18: PBs and corresponding Quotas

7.5 Conclusions

In this chapter, nine Planetary Quotas have been derived conceptually from the Planetary Boundaries. There is not a one to one relationship between the PBs and the PQs, but together, the PQs define the limits for human activity that are needed to return to and remain within the PBs.

The methodology used is based on multi-disciplinary methodologies. The specific methods build on previous works which used the DPSIR framework to disaggregate the Planetary

Boundaries into corresponding pressures. The method shown here advances previous methods through the inclusion of strategies to accommodate the interconnectivity of the PBs and to allow for the consolidation of pressures where these are equivalent with respect to corresponding Boundaries.

Having created the structure of the methodology it is now possible to create scalable Planetary Quotas. The following sections describe the detailed translation of each PB to a scalable parameter.

SECTION 3

CHAPTER 8

A Planetary Quota for Carbon Dioxide

Abstract

Carbon dioxide emissions are the primary human pressure on the environment causing the global average temperature to increase. There are many other human factors which also contribute to global temperature change in both positive (warming) and negative (cooling) ways. These include the emissions of other greenhouse gases, the changing reflectivity of Earth's surface due to land-use change, and the cooling effect of suspended particles in the atmosphere emitted during human activity.

There are two limits in the Planetary Boundaries framework which address climate change. One, is for a maximum change in radiative forcing, the energy balance in the atmosphere, to account for the many drivers of climate change. The other is for the concentration of carbon dioxide in the atmosphere of ≤350ppm. The explicit limit for carbon dioxide in addition to the limit for radiative forcing highlights the importance of this gas to the function of the planet.

The current concentration of carbon dioxide in the atmosphere is ≥400ppm, i.e., the limit has been exceeded. Thus, to return to the Planetary Boundary level, carbon dioxide will need to be withdrawn from the atmosphere.

There are several proposals in the academic literature for ways to reduce the concentration of carbon dioxide in the atmosphere to 350ppm. The fastest pathway, and the only one that achieves 350ppm within this century entails aggressive reductions in carbon dioxide emissions of 15% per year from 2020; an average uptake of carbon dioxide of 7.3GtCO_2 each year from 2050 – 2080, and net zero emissions beyond 2080.

The Planetary Quota for carbon dioxide is thus *net carbon emissions* ≤ -7.3GtCO_2/year. This limit can be compared to the net carbon footprint of any scale of human activity. If emissions reductions in the scale of 15% per annum do not start by 2020, this limit will need to be revised to reach 350ppm this century.

8.1 Introduction

In Chapter 7, critical pressures – human induced burdens on the environment – were identified for each Planetary Boundary (PB) limit. Planetary Quota (PQ) indicators were determined for each critical pressure or group of critical pressures where grouping was deemed appropriate. Table 10, Chapter 7 lists the nine PQ indicators against corresponding critical pressures and PB limits.

This chapter introduces the PQ for carbon dioxide (CO_2) emissions. Table 11 is a modified excerpt from Table 10, Chapter 7. It shows that there is only one critical pressure pertaining to this PQ, but that there are five corresponding PBs. This means that the PQ limit for CO_2 emissions must respect each of these five PBs.

Table 11: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicator, critical pressure, and corresponding PB indicators and limits

PQ Indicator	Critical Pressures	Corresponding PB
Carbon dioxide emissions	Carbon dioxide emissions	Concentration of CO_2 in the atmosphere ≤ 350ppm[a] Radiative forcing ≤1W/m^2 Saturation state of aragonite ≤ 2.75 Extinction rate ≤ 10 E/MSY[b] Remaining forestland ≥ 75% original

Notes:

a. ppm – parts (of CO_2) per million parts (of atmosphere)
b. E/MSY – extinct species per million species per year

This chapter begins with an introduction to the carbon cycle and a discussion about why there is a specific PQ for CO_2 emissions, as opposed to a PQ for all greenhouse gases. This is followed by an overview of ways to measure CO_2 emissions and the argument for selecting *net carbon footprint* as the indicator. The chapter goes on to discuss the PQ limit with respect to each of the corresponding PBs shown in Table 11 to show how the limit has been derived. The chapter concludes with a discussion of current emissions with respect to the PQ, and some examples of what might be needed to make the changes required to live within this PQ.

8.2 Background

8.2.1 The Carbon Cycle

The Earth System has several biogeochemical cycles, in which a chemical substance moves between the biosphere (life on Earth), lithosphere (Earth's crust), atmosphere (the layer of gases surrounding Earth), and hydrosphere (surface and atmospheric water). Carbon, oxygen, nitrogen, water, and phosphorous all have biogeochemical cycles – many of which are described in this thesis.

The carbon cycle (see Figure 19) can be viewed as two separate but linked cycles. In the first cycle, carbon moves relatively quickly between the atmosphere, ocean, ocean sediments, vegetation, soil, and fresh water. In the second cycle, carbon contained in dead plant and animal matter is buried under layers of sediment and over hundreds of thousands of years, gradually turns to coal, oil, and natural gas. (Ciais et al., 2013b)

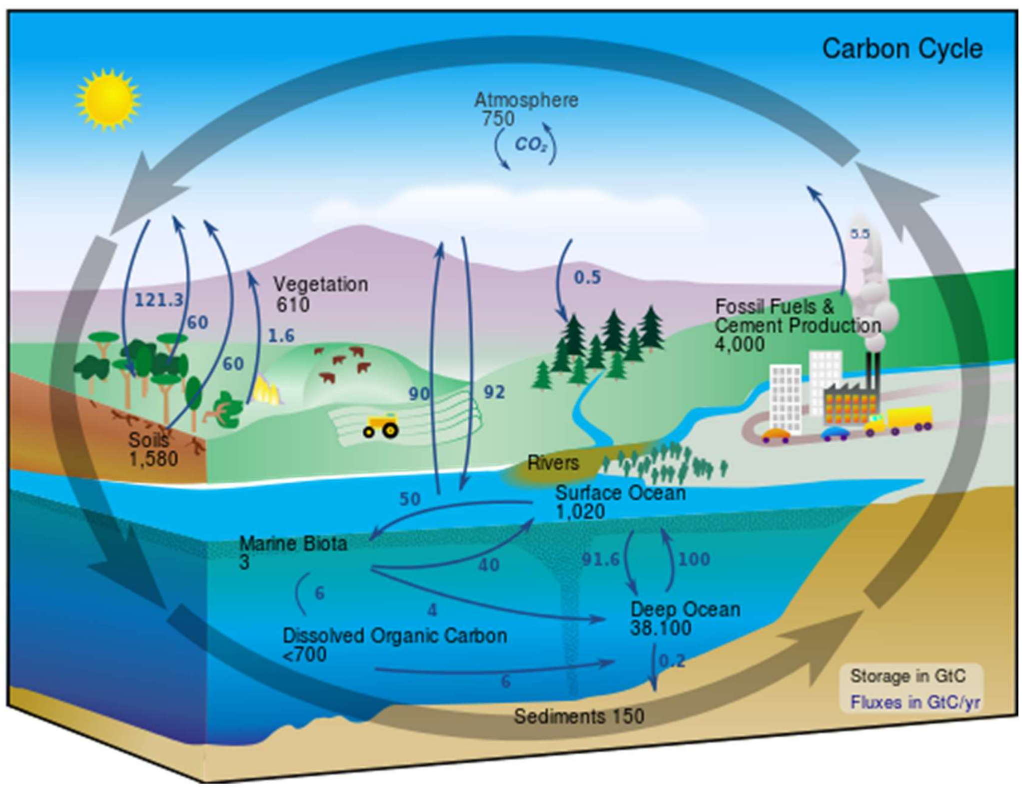

Figure 19: The carbon cycle ((Saff, 2008) PD[15])

From the beginning of the Holocene epoch[16], until the industrial revolution approximately 11,500 years later, the concentration of CO_2 remained relatively constant at approximately

[15] PD: This image has been released to the public domain

[16] The Holocene epoch is a period of time that started approximately 10,000 years ago. See Chapter 1 for more detail.

280 parts of CO_2 per million parts of atmosphere (ppm). Since the industrial revolution, human activity, in particular the burning of fossil fuels, the manufacture of cement, and deforestation, has led to a rapid increase in the concentration of CO_2 in the atmosphere. The atmospheric concentration of CO_2 is now over 400ppm (NOAA, 2018b). Concentrations have not been this high in at least 800,000 years (WMO, 2017b). Some estimates suggest that it has not been this high for 15 million years (Tripati et al., 2009). It is practically certain that concentrations of CO_2 have not been this high in human history – which spans approximately 380,000 years.

Since the industrial revolution, in the same period that there has been a substantial increase in the atmospheric concentration of CO_2, there has been an increase in global average of just over 1°C (NASA, 2017). The concern over increasing levels of CO_2 in the atmosphere is that there is very strong evidence that the atmospheric concentration of CO_2 is linked to global average temperature (see Chapter 2, Section 2.3.1). There is a time lag between CO_2 emissions and temperature change so that even if we stopped emitting CO_2 today, the world would continue warming. The more CO_2 emitted, the more warming we are likely to experience.

Historic data suggests that average temperatures and CO_2 concentrations do not change gradually and linearly. In the past, changes have started gradually until a tipping point has been reached at which point changes have become very rapid. If we reach a certain threshold of CO_2 concentration we risk putting into motion dramatic and potentially irreversible change to the Earth System. These tipping points occur because of natural feedback loops (see Chapter 2, Section 2.3.1).

8.2.2 The need for a specific Planetary Quota for Carbon Dioxide

There are many human factors that contribute to climate change – i.e., change in global average temperature. Anthropogenic emissions of carbon dioxide (CO_2) is only one factor, but it is also the single biggest contributor to climate change (IPCC, 2013d) and needs particularly careful management (Steffen et al., 2015). Other human factors include greenhouse gas (GHG) emissions, stratospheric and tropospheric ozone, water vapour, surface albedo (the reflectivity of the Earth's surface) and atmospheric aerosols (IPCC, 2013c). There are two Planetary Boundaries (PBs) for climate change:

- Atmospheric concentration of $CO_2 \leq 350$ ppm
- Radiative forcing $\leq \pm 1.0$ W/m^2

The limits correspond to a temperature increase of approximately 1.7˚C above pre-industrial times (Hansen et al., 2008). The first limit pertains solely to CO_2. The second provides a more all-encompassing limit that considers not only CO_2 but also the other factors which influence climate change. When the Planetary Boundaries were first published, the concentration of CO_2 in the atmosphere was 387 ppm (Rockström et al., 2009a). Now, in 2018, the concentration is over 400 ppm (NOAA, 2018b). The change in radiative forcing since pre-industrial times is approximately +1.5 W/m^2 (Myhre et al., 2013a).

<u>Box 8.1: Why 350ppm?</u>

The current concentration of CO_2 in the atmosphere is 400ppm. This begs the question "Why the is the PB for CO_2 concentration set at 350ppm?"

There is a lag between the change in concentration of CO_2 and the change in global temperature. This means that even if we stopped emitting any greenhouse gases today the world would continue warming for some time.

The PB for atmospheric concentration of CO_2 has been set at a level which is thought to minimise the risk of "highly non-linear, possibly abrupt and irreversible" change. This is based on data which suggests that that the planet was mostly free of ice until CO_2 concentrations fell to somewhere between 350 – 550ppm (Hansen et al., 2008).

The authors of the PBs justify locating the limit on the lower end of this range because there is evidence that the Earth's subsystems are already starting to behave differently than they did in a Holocene state (Rockström et al., 2009b). Moreover, the authors' review of existing climate models led them to believe that the models do not adequately take into account the severity of feedback loops (Rockström et al., 2009b).

Climate change is complex. Greenhouse gas emissions warm the atmosphere by absorbing infrared radiation and thus trapping heat in the atmosphere. Atmospheric aerosols (tiny particles suspended in the atmosphere) can both warm the atmosphere by trapping heat and cool the atmosphere by reflecting it. Changing the Earth's surface can warm or cool the atmosphere by changing the albedo (or reflectivity) of the surface. For example, the less surface area covered by ice (the most reflective surface on Earth) the more warming occurs. Even within a single "type" of climate change factors, for example GHG emissions, there is not one single mechanism for warming. Carbon dioxide behaves differently to methane which behaves differently to nitrous oxide. The effects of different forcing elements are shown in Figure 20.

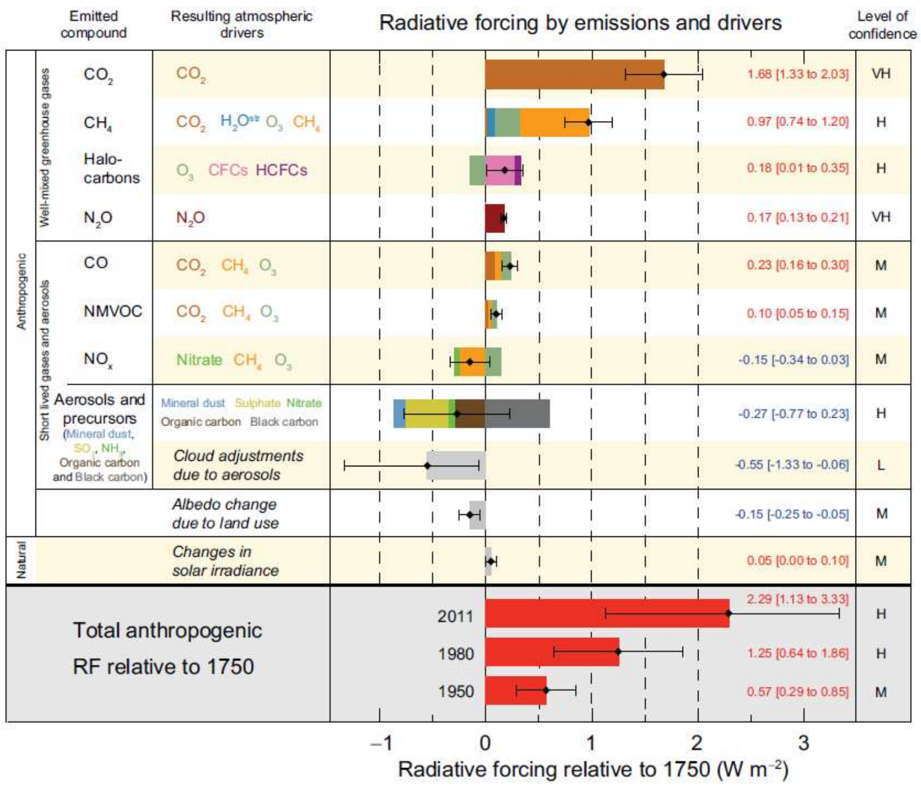

Figure 20: Radiative forcing impacts of different compounds and atmopheric drivers resulting from the emitted compounds relative to 1750 (Figure SPM.5 from (IPCC, 2013d)[17])

To simplify the situation, two main indicators have been developed to allow the direct comparison of different forcing agents.

1. Radiative Forcing (RF): Radiative Forcing is defined by the IPCC (2013d) as the change in energy flux at the top of the atmosphere caused by a forcing agent. Radiative forcing can be determined based on a change in concentration of a substance in the atmosphere, or based on the amount of emissions of the substance (Pierrehumbert, 2014). It can also be used to assess forcing effects due to the albedo of clouds and Earth's surface. It is measured in Watts per square metre. This metric is very useful as it allows the effects of greenhouse gases to be compared to the effects of aerosols and change in albedo as shown in Figure 20. There is a proportional relationship between the change in equilibrium surface temperature and radiative forcing (Myhre et al., 2013b).

[17] IPCC allows the reuse of a small number of figures without formal permissions with appropriate acknowledgement

2. Global Warming Potential (GWP): This unit allows emissions of GHGs to be communicated in terms of *equivalend* kilograms (or tons) of CO_2 (CO_2e). The equivalency is determined by the global warming potential (GWP) of each gas. The GWP is the amount of heat trapped by a substance in a specified timeframe (typically 100 years), compared to the amount of heat trapped by the same amount of carbon dioxide. The GWP of nitrous oxide is 256-298 over a timescale of 100 years. This means that burning 1kg of nitrous oxide will have the same warming effect over 100 years as burning between 256 - 298 kg of carbon dioxide.

It is common practice to use GWP to measure greenhouse gases collectively (Greenhalgh et al., 2005). After the Kyoto Protocol was initiated, the practice of GHG accounting – measuring and reporting greenhouse gases - became formalised and standardised so that countries could demonstrate whether or not they were meeting their commitments under the protocol and be held accountable for this. In formal GHG accounting procedures the impacts of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) must all be accounted for.

International standards for measuring impacts of greenhouse gases assume an equivalency between carbon dioxide and other greenhouse gases. Yet, the authors of the PB framework specified a specific CO_2 limit – implying that CO_2 emissions are not equivalent to other climate forcings from a global limit perspective. The indicators RF and GWP allow us to consider different forcing agents in the same framing. However, despite the terminology of the GWP unit of measure – CO_2 *equivalence* – the impacts are not equivalent in the long term because they have very different atmospheric lifetimes. Carbon dioxide, nitrous oxide, methane, and some halocarbons are all considered to be “long-lived” greenhouse gases. The definition of “long” in “long-lived” varies substantially.

As shown in Figure 20 CO_2 has had the greatest contribution to climate forcing since 1750. It will also continue to have the greatest contribution, not only because of the high level of past and predicted emissions, but also because we will continue to experience the warming effects of past CO_2 emissions for tens of thousands of years. As discussed above, the carbon cycle has a rapid sub-cycle and a slow sub-cycle. The problem is that in the last 50-100 years, humans have extracted billions of tonnes of carbon from the slow domain and released it into the fast domain, disturbing the natural balance. To restore the balance, the carbon we have released will need to be returned to the slow cycle. This will happen naturally over tens of thousands of years. CO_2 can actively be removed from the environment through vegetation and forestation (IPCC, 2013e), or through geoengineering (Druckman and Jackson, 2010), but not at the rates we are currently emitting it.

In contrast, the atmospheric lifetime of methane in the atmosphere is estimated to be 7-11 years (IPCC, 2013b), nitrous oxide, 118 – 131 years (Volk et al., 1997, Hsu and Prather, 2010, Fleming et al., 2011). The warming potential of these gases is higher per kilogram that CO_2. However, emitting these substances does not have the same long-term commitment to warming as emitting CO_2. It is thus not equivalent to emit 1 kg of nitrous oxide to 298 kgs of CO_2. To have a low risk of departure from a Holocene-like state, and to respect the Planetary Boundaries, CO_2 will need to be removed from the atmosphere. Thus, a specific PQ for CO_2 is required.

8.3 An Indicator for Carbon Dioxide Emissions

The term carbon footprint originated from the concept of an Ecological Footrprint (Sundha and Melkania, 2016). In its broadest sense, a carbon footprint is the amount of carbon (or carbon equivalents) emitted by a group, or over the course of an activity (e.g. the manufacturing of a product). Carbon footprint tools are extensively used in a wide range of applications from basic online calculators to detailed life-cycle analyses of products, regions or nations (Sundha and Melkania, 2016, Wright et al., 2011). The concept of a carbon footprint forms the underpinning of carbon accounting. Specific carbon footprint definitions range from a measurement of CO_2 emissions to a measurement of all greenhouse gas emissions and can be reported in terms of tons of CO_2, tons of CO_2 equivalent, or sometimes in terms of the forest area which would be required to absorb the CO_2 (Cucek et al., 2012). It is common practice to report gross emissions of CO_2 and uptake of CO_2 from land-use change and forestry separately. However, combing these figures is sometimes done to report *net carbon dioxide emissions.*

In the selection of an appropriate PQ indicator for CO_2 it is important to consider that to return to the PB level for CO_2 will mean withdrawing CO_2 from the atmosphere. The Quota for CO_2 must thus be communicated in a unit that can be positive or negative. The proposed indicator for the PQ for CO_2 is therefore *net CO_2 emissions* measured in kg of CO_2. The global PQ can then be compared to the net CO_2 footprint of any scale of human activity.

8.4 The Limit

There are four upstream PBs that were considered when deriving the PQ for CO_2 (as shown in Table 11):

- climate change: atmospheric concentration of CO_2 ≤ 350ppm;
- climate change: total radiative forcing ≤ ±1W/m^2;
- ocean acidification: aragonite saturation state of the oceans ≥80% of the pre-industrial level; and
- biosphere integrity: global extinction rate ≤ 10 E/MSY.

8.4.1 Total Radiative Forcing

As discussed in Section 8.2.2, total radiative forcing is the most holistic measure of global warming/cooling and accounts for all GHG emissions as well as change in albedo (reflectivity of Earth's surface which changes with land-use change) and the emission of aerosols (particles suspended in the atmosphere). Emissions of CO_2 alone have resulted in an RF of 1.68 W/m^2 (IPCC, 2013d). There are four PQs which contribute to total radiative forcing: the PQs for carbon, methane and nitrous oxide ("Me-NO"), reforestation, and aerosols. It is not possible to derive a specific limit for any one factor which contributes to radiative forcing in isolation – the limit is a collective value. The collective forcings and the way in which the four PQs resect the PB limit for radiative forcing are discussed in Chapter 12.

8.4.2 Ocean Acidification

The oceans absorb CO_2 from the atmosphere at a rate that is loosely proportional to the concentration of CO_2 in the atmosphere. This process has significantly dampened the warming effects of anthropogenic CO_2 emissions. However, the absorption of CO_2 by the oceans has also increased the ocean pH levels. This means that the seas are more acidic which has disastrous impacts on marine ecosystems. Marine ecosystems are critical to the functioning of the Earth System (Rockström et al., 2009a) and thus ocean acidity is an important Planetary Boundary. However provided the PB for CO_2 concentration is respected, the PB for ocean acidification will also be respected (Steffen et al., 2015). As such, it follows that provided PQ for CO_2 respects the PB for CO_2 concentration, the PB for ocean acidification is also intrinsically respected.

8.4.3 Biosphere Integrity

Climate change is one of five key pressures leading to the loss of species (Secretariat of the CBD, 2001). There is no specific concentration of CO_2 or level of climate change considered "safe" with respect to extinction rate. It is assumed that the PB limits for climate change are adequate to address species loss due to climate change. Thus, the pressure of climate change on biosphere integrity is managed provided the PQs respect the PBs for climate change.

8.4.4 CO_2 Concentration

The rate of CO_2 uptake required to return atmospheric CO_2 concentration to 350ppm depends on the timeframe. There are several articles in the scientific literature proposing pathways of rapid decarbonisation – i.e., pathways that will result in a reduction in atmospheric CO_2 concentration from today's levels by the end of the century. These are summarised in Table 12 and described in more detail below.[18]

[18] There is a fourth scenario by ACKERMAN, F., STANTON, E. A., DECANIO, S. J., GOODSTEIN, E., HOWARTH, R. B., NORGAARD, R. B., NORMAN, C. S. & SHEERAN, K. A. 2009. The Economics of 350: The Benefits and Costs of Climate Stabilization. Economics for Equity and the Environment Network, Ecotrust, Stockholm Environment Institute. based on rapid emissions reductions without relying on CO_2 uptake. They estimate that the concentration of CO_2 in the atmosphere will drop to 350ppm by 2200 in their scenario. This scenario has not been analysed here as there is no data available to show the detail of their pathway. Further, this pathway returns to the PB limit much later than Hansen's 500GtC pathway so is unlikely to be a preferable option.

Table 12: Comparison of pathways for rapid decarbonisation

Pathway	Description	Predicted Concentration in 2100 (ppm)	Maximum annual reduction between 2018 and 2100 ($GtCO_2$/yr)	Average emissions between 2018 and 2100 ($GtCO_2$/yr)
RCP2.6 (van Vuuren et al., 2011)	Rapid reduction of CO_2 emissions until 2100, followed by constant negative emissions of approximately -1 $GtCO_2$/yr for the following century, followed by constant negative emissions of approximately -1 $GtCO_2$/yr for the following century	400	-1.5	1.56
500GtC (Hansen et al., 2013a)	Rapid emission reductions (129 GtC cumulative from 2013-2050 and a further 14 GtC from 2050-2100) with 100GtC uptake. The carbon uptake under this scenario is through reforestation – to achieve 1.6 GtC uptake per year, and technologies such as biochar storage, to achieve a further 0.16 GtC/yr (Hansen et al., 2008)	350	-7.3	-0.57
The Carbon Law (Rockström et al., 2017)	Net cumulative emissions of 190GtC from 2017 – 2100 with un uptake of 136GtC in the same period	380	-16.3	11.89

8.4.5 RCP2.6

In the fifth assessment report by the International Panel for Climate Change (IPCC) four *representative concentration pathways* (RCPs) have been proposed to show different future emissions scenarios. RCP2.6 is the most stringent of these scenarios. Of the four carbon scenarios in the IPCC's Fifth Assessment Report, only RCP2.6 is unlikely to exceed a 1.5°C temperature increase relative to 1850-1900 by the end of the 21st century (IPCC, 2013d). For all scenarios except RCP2.6, warming will continue beyond 2100 (IPCC, 2013d).

Under the RCP2.6 scenario atmospheric levels of CO_2 are expected to continue to rise, reaching 421 ppm by 2100 (see Figure 21). The likely temperature increase under this scenario is 0.3-1.7 °C by the end of the century with a global mean sea level rise 0.26 – 0.55 m in the same period (IPCC, 2013d). Total radiative forcing in this scenario peaks at approximately 3 W/m^2 before 2100 and then declines to 2.6 W/m^2 by 2100.

After 2100 RCP2.6 shows constant negative emissions of approximately -1 $GtCO_2$/yr for the following century. 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). RCP2.6 does not achieve either of the PB thresholds within this century or the following. This pathway would return us to within the Planetary Boundary level for CO_2 concentration around 2500 (van Vuuren et al., 2011).

8.4.6 500 GtC

Former NASA Chief Climate Scientist, James Hansen, and colleagues proposed a pathway which would return CO_2 levels to 350 ppm by 2100. The authors propose that cumulative industrial era emissions must be limited to 500 GtC (hence the name of this pathway) and that carbon uptake of 100 GtC will also be required this century. This is the fasted pathway to 350 ppm and the only one proposed that is estimated to return CO_2 concentrations to the PB level this century.

The original pathway proposed by the authors is based on CO_2 emissions reductions starting in 2015. In 2018, it is thus too late to follow this pathway. However, the authors discussed the implications of a later start date – with emissions reductions of 2020. It is this scenario that is presented here (see Figure 21):

- Annual reductions of 15% from 2020 – 2050;
- Net uptake of 7.3 GtC/yr from 2050 – 2080 and net zero emissions beyond 2080, achieved by:
    - A maximum of 14 GtC to be emitted cumulatively from 2050 – 2100;

- Rapid reforestation, improved agricultural practices, and CO_2 drawdown through bio-fuels to remove 100 GtC gross from 2013 – 2100). The authors suggest that this should be achieved by rapid reduction in deforestation to net zero by 2030 followed by increasing carbon withdrawals to achieve 100 GtC net by 2100.

8.4.7 The Carbon Law

The Carbon Law was proposed by Rockström et al. (2017). The "law" is that emissions should halve every decade. This scenario begins with less severe emissions reductions than the 500 GtC pathway in the near term with reductions of approximately 4% per year until 2030. The reductions increase from 2030 – 2050 to 5% - 11% per year and drop back to 3-4% from 2050 – 2100. The Carbon Law pathways includes a much bigger proportion of carbon extraction later this century then the 500 GtC pathway to make up for the slower start in emissions reductions. The authors estimate that this pathway would result in a CO_2 concentration of approximately 380 ppm by 2100 – still beyond the Planetary Boundary of 350 ppm.

8.4.8 Comparison

The net annual emissions (including CO_2 emissions (or uptake) from land use and land-use change) of these three pathways are shown in Figure 21.

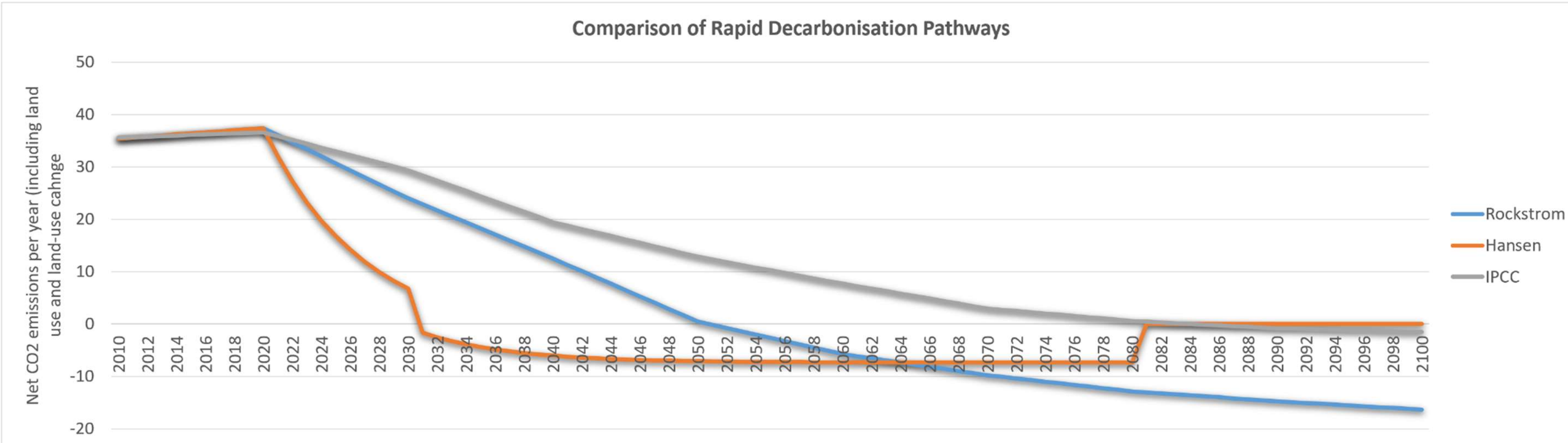

Figure 21: Net annual CO_2 emissions proposed for decarbonisation pathways to return to CO_2 concentrations of 350 (Hansen et al), 380ppm (Rockstrom et al) and 420ppm (RCP2.6) by the end of the century

RCP2.6 does not even get close to the PB limit this century so is considered insufficient. The Carbon Law pathway comes close to the PB limit by the end of this century with far less challenging near-term reductions. However, this pathway relies on uncertain technology, and it delays action. If the technologies are not developed in time, the emissions reductions that would be required to make up for the slow start under this scenario, would likely be far more difficult to achieve than the immediate targets under the 500 GtC.

The 500 GtC pathway is the most immediately aggressive, and the only pathway predicted to reach the PB limit for CO_2 concentration this century. As such, the PQ limit is based on this scenario as *net CO_2 emissions* ≤ -7.3 $GtCO_2$/yr.

The intention of the Planetary Quotas is to define end goal targets and not the pathways to reach these. Determining a single value for the PQ for CO_2 based on a pathway that varies over time requires a degree of value judgement. The decision to set the limit at this point is based on two key points:

1. This is the highest rate of CO_2 uptake required; and
2. This is the approximate rate of uptake for 30 years.

This level can thus be considered the "end goal" in that it is the most difficult target for CO_2, and it is one that needs to be sustained over time.

The PQs are all based on the Planetary Boundaries as they are today. It is likely that these will change over time and that many of PQs will need to be updated accordingly. This is particularly true for the PQ for CO_2. When Hansen et al (2013a) first proposed the 500 GtC pathway in 2013, they estimated that only 6% reductions would be required each year from 2015. Delaying the start of the reductions by 5 years resulted in an increase to 15% per year to achieve the same result. The PQ proposed is on the basis that:

1. Rapid CO_2 emission reductions must begin by 2020 at the latest;
2. Net CO_2 emissions must reach zero by 2030;
3. The PQ of -7.3 $GtCO_2$ much be reached by 2050.

If this does not occur, the PQ for CO_2 will need to be revised.

8.5 Discussion

The PQ for CO_2 emissions of -7.3 $GtCO_2$/yr is an ambitious target. Global annual emissions are currently in the order of 36 $GtCO_2$/yr (World Bank, 2009). At a projected population of 9 billion, the PQ for CO_2 equates to an average carbon footprint of -0.8 tCO_2/person/yr. To put this into context, the average carbon footprint of the OECD countries is currently 11 tCO_2/person/yr; an average car emits approximately 4.7 tCO_2/year; and a return flight from NZ to London for one person equates to emissions of approximately 7.5 tCO_2.

In 2016, after almost a century of increasing emissions, the global emissions did not increase. In fact, for three years in a row, from 2014 – 2016 the global CO_2 emissions remained relatively constant. In 2017 emissions rose again (NOAA, 2018c), meaning that CO_2 emissions have not yet peaked. However, the trend in the past 10 years suggests that the rate of increase in carbon emissions is dropping.

Table 13 shows examples of how this PQ could be put into practice at different scales of activity and across different sectors. The examples relate to varying timeframes.

The timeframe to reduce net emissions to zero to meet the criteria for this PQ is only 10 years. This is very ambitious. However, the journey is not only starting now. Humans have been trying to manage CO_2 emissions for several decades already. Moreover, humanity has made dramatic changes in both technology and behaviour over very short periods of time before. For example, consider the mobile phone. The first portable phone – the DynaTAC, was available in the early 1980s. For 27 years, there were regular advancements – phones became smaller, batteries lasted longer. There was continual improvement at a fairly constant rate. Then in 2007 the first smart phone was introduced – the iPhone – an all-in-one phone, camera, music player, and internet enabled PDA. Now, approximately 10 years later, almost 90% of the world's population is covered by 2G networks and over 2 billion people, more than a quarter of the world's population, own smart phones.

Table 13: Examples of different scales of activity which have or could contribute to achieving the PQ for CO_2 emissions

Achieving the Planetary Quota for CO_2 Emissions			
Large	Development of an independent global community to report on the scientific understanding of CO_2 emissions and corresponding impacts *e.g., the International Panel for Climate Change*	Develop a global treaty to limit carbon emissions *e.g. the Paris Agreement*	Develop innovative solutions for the removal of CO_2 from the atmosphere
Medium	Lobby government to go carbon neutral *e.g. youth led community organisation Generation Zero (NZ) who drafted a law that would commit NZ to carbon neutrality by 2050*	Implement rail, walk ways, cycle paths	Install solar panels to power business operations
Small	Install a community renewable energy system with battery storage *e.g. White Gum Valley*	Encourage car pool schemes	Go fossil fuel free
Individual	Behaviour change: Choose a fossil fuel free electricity provider Switch to an electric vehicle Turn off lights Eat less meat	Develop new models for a low carbon economy *e.g. Peter Newman developed a new financial model to make city rail affordable*	Disruptive low carbon innovations *e.g. Elon Musk developped battery technology which is helping to accelerate the transition to a fossil fuel free economy*
	Community	**Government**	**Business**

8.6 Conclusion

The impacts of carbon dioxide emissions cannot be offset by reductions in other greenhouse gas emissions because of the long atmospheric lifetime of carbon dioxide. This is reflected in the Planetary Boundaries through the specific limit for the concentration of CO_2 in the atmosphere. The PB has been exceeded, as such the PQ is negative – i.e., carbon dioxide must be withdrawn from the atmosphere. The PQ for CO_2 is *net carbon emissions* ≤ -7.3 $GtCO_2$/yr. This is based on a pathway that is estimated to return the concentration of CO_2 in the atmosphere to within the PB limit for CO_2 by the end of this century.

CHAPTER 9

A Quota for methane and nitrous oxide (Me-NO)

Abstract

Excessive human emissions of GHGs are one of the "forcing" factors that has contributed to a change in global average temperatures by changing the balance of radiation at the top of Earth's atmosphere. Other anthropogenic forcing factors include change in albedo (Earth's reflectivity) due to land-use change, and the emissions of aerosols and aerosol precursors. There is a Planetary Boundary for the change in radiative forcing since pre-industrial times of ≤ ±1W/m^2.

Carbon dioxide, methane, nitrous oxide, and halocarbons are called "long lived" or "well-mixed" gases. This means that they remain in the atmosphere long enough that the location of the source of the emissions is irrelevant. The impacts are experienced on a global scale. The warming effects of long-lived gases can all be expressed in terms of equivalent emissions of carbon dioxide (CO_2e). However, of these gases, only methane and nitrous oxide can be considered collectively in one Planetary Quota.

To operate within the Planetary Boundaries will require a net withdrawal of carbon dioxide from the atmosphere and a phase out of halocarbons to zero emissions. In contrast, it is possible continue to emit a small amount of methane and nitrous oxide without exceeding the limits. Thus, emissions of carbon dioxide are considered under a specific PQ for carbon dioxide which is negative; halocarbon emissions are considered within the PQ for Montreal gases which is zero; and methane and nitrous oxide, "Me-NO", are considered together here under this PQ.

The PQ for Me-NO is *gross emissions of Me-NO* ≤5 $GtCO_2e$/yr. This limit can be compared to the gross emissions of Me-NO associated with any scale of human activity. The limit is based on the 2100 targets for these gases under the most stringent emissions reduction pathway proposed by the International Panel for Climate Change. The 2100 values were estimated based on optimising the conflicting goals of minimising emissions of Me-NO whilst maximising agricultural output per land area.

9.1 Introduction

Methane and nitrous oxide are two of the four "well-mixed" greenhouse gases (GHGs) listed as critical pressures in Chapter 7. The other two are carbon dioxide and halocarbons. As discussed in Chapter 8, GHGs are gases which trap heat in Earth's atmosphere. This is because they are transparent to longwave radiation (the radiation that comes directly from the sun) but reflect shortwave radiation (the radiation the bounces back from Earth's surface and clouds) thus trapping the radiation into the atmosphere. The term "well-mixed" refers to the relatively long atmospheric lifetime of the gases which means that they disperse throughout the global atmosphere. Another term for this is "long-lived" GHGs.

In Chapter 7, the critical pressures for each of the Planetary Boundaries were grouped based on equivalency where possible. Of the four long-lived greenhouse gases, only methane and nitrous oxide have been grouped with one-another. This chapter begins with an introduction to the methane and nitrous oxide cycles, and a brief history of human use of these gases. This is followed by the rationale behind the indicator used for this Quota and the scientific basis for the PQ limit. The chapter concludes with a discussion about the PQ for MeNO and the types of actions that may help humanity to live within this.

Table 14 shows the PQ indicator and these pressures against the corresponding PB limits that this PQ must respect. The term "methane and nitrous oxide emissions" is long. However, there is no collective term for these two gases. Thus, for simplification, I refer to these collectively as "MeNO" emissions (**me**thane and **n**itrous **ox**ide) here on.

The emissions of these gases are two of the biggest contributors to global climate change (IPCC, 2014b). They are emitted during the combustion of fossil fuels, from agriculture and agricultural practices, and because of some types of land use and land-use changes (Ciais et al., 2013a). Current concentrations of these gases exceed levels measured for at least 800,000 years and the rate of change of emissions increased more in the last 100 years than any rate over the past 20,000 years (Ciais et al., 2013a).

This chapter begins with an introduction to the methane and nitrous oxide cycles, and a brief history of human use of these gases. This is followed by the rationale behind the indicator used for this Quota and the scientific basis for the PQ limit. The chapter concludes with a discussion about the PQ for MeNO and the types of actions that may help humanity to live within this.

Table 14: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicator, critical pressures, and corresponding PB indicators and limits

PQ Indicator	Critical Pressures	Corresponding PB
MeNO emissions	Methane emissions Nitrous oxide emissions	Radiative forcing ≤1 W/m^2 Extinction Rate ≤ 10 E/MSY[a] Concentration of stratospheric ozone ≥ 290 (Dobson units)[b]

Notes:

a. E/MSY – extinct species per million species per year
b. This PB only corresponds to nitrous oxide – this is discussed further in section 9.5

9.2 The Methane Cycle

Methane (CH_4) is generally considered to be the second most important greenhouse gas after carbon dioxide. The warming potential of nitrous oxide is higher than that of methane per kilogram of emission. However, human activities are responsible for a substantially higher amount of methane emissions. The radiative forcing of methane since pre-industrial times is approximately 0.97 W/m^2 (Myhre et al., 2013b). This means that since 1750, methane emissions have increased the energy flux at the top of Earth's atmosphere by approximately 1 W/m^2. To put this into context, the total change in radiative forcing since 1750 is approximately +1.5 W/m^2 (Myhre et al., 2013a). The change in radiative forcing due to carbon dioxide is 1.68W/m^2 and from nitrous oxide emissions it is 0.18W/m^2.

Methane is a naturally occurring gas in Earth's atmosphere. Before the industrial revolution, methane made up approximately 722 parts per billion parts of atmosphere (ppb). Biological methane is emitted during the fermentation of organic matter in low oxygen conditions. Natural biological methane is emitted by wetlands, bacteria, termites, and a small amount from the oceans. There are also natural sources of fossil methane (methane stored under Earth's crust). This can be released into the atmosphere via terrestrial leeks, geothermal vents, forest fires, and volcanic eruptions.

Methane is removed from the atmosphere naturally through photochemistry with hydroxyl radicals. It is thought that smaller amounts of methane are also removed through reactions with chlorine and oxygen radicals, by oxidation in aerated solids, and through reactions with chlorine in the marine boundary layer. (Allan et al., 2007)

The greatest anthropogenic source of methane is biological emissions from agriculture and land-use change. Rice paddies, livestock, landfill off-gassing, man-mad lakes and wetlands, and waste treatment plants are all examples of biological anthropogenic sources of methane. Fossil methane can be leaked during the extraction and use of fossil fuels. Anthropogenic fires, i.e., burning plant biomass, also releases methane emissions (Conrad, 1996).

Between 1750 and 2011, methane concentrations have increased from 722ppb to 1803ppb (Myhre et al., 2013b). From 1750 until the mid-1980s the increase was almost exponential. However, from the mid-1980s the atmospheric concentrations of methane stayed relatively constant for about 20 years. This is thought to have been caused by a decline in biomass burning (Rice et al., 2016). More recently, since 2006, there have been increases in the atmospheric concentration of methane again (Rigby et al., 2008). It is uncertain whether this is likely to continue or not (Dlugokencky et al., 2009).

Scientists have shown with very high confidence[19] that the increase observed from 1750 to the 1980s was caused by humans (Ciais et al., 2013a). Methane emissions caused by human activity in 2013 account for between 50-65% of total global emissions of methane. Concentrations of methane have been found to be higher downwind of intensive agricultural areas, providing further evidence of the impacts of human methane emissions (Frankenberg et al., 2011).

Like carbon, there are feedback loops associated with the methane cycle. One feedback loop of particular concern pertains to large stores of methane stored in shallow ocean sediments, on the slopes of continental shelves, and in permafrost soils. These are all stable under current temperatures. However, methane emissions contribute to warming which can lead to melting ice thus releasing these stores. This would in turn lead to further warming and so on. (Ciais et al., 2013a)

9.3 Nitrous Oxide

Nitrous Oxide (N_2O) is the third most important greenhouse gas. It is a very small component of Earth's atmosphere with a concentration of only 0.33 parts per million parts of atmosphere (ppm). This concentration is 1.2 times higher than the concentration before the industrial revolution. (Myhre et al., 2013a)

Nitrous oxide is released during the natural nitrogen cycle. The largest natural source of nitrous oxide is the soil. Nitrifying and denitrifying bacteria release nitrous oxide as a by-product (see Chapter 14), which accounts for approximately 60% of natural emissions of

[19] This is a term used by the International Panel for Climate Change (IPCC) to denote specific scientific probabilities. The term "very high confidence" conveys a 9/10 chance of being correct. See "Table of Confidence Intervals" in the Glossary of Terms for the full set of IPCC scientific probability terminology.

nitrous oxide (Denman et al., 2007). The remaining emissions come from the oceans (35%) and atmospheric chemical reactions (5%).

Like methane, agriculture is the greatest anthropogenic source of nitrous oxide. Fertilised soil and manure contribute 42% of emissions, runoff and leaching of fertilisers are another 25%. Biomass burning 10%, fossil fuel combustion 10%, biological degradation 9% and sewage 5%. (IPCC, 2007)

It can be very difficult to measure nitrous oxide emissions as most agricultural emissions come from bacteria in the soil and because the emissions can vary substantially with weather.

9.3.1 Laughing Gas

Joseph Priestley, an English Philosopher, synthesised nitrous oxide in the late 1700s. He called phlogisticated nitrous air, or inflammable nitrous air. Not long after this the use of nitrous oxide for medical purposes began. It was used in anaesthetics from the mid-1800s, and later as a recreational drug when it was found to put people into a state of euphoric laughter. It is still used in modern medicine (see Box 9.1).

> Box 9.1: N_2Ot so funny gas
>
> I was given nitrous oxide to help ease the pain of labour when trying to deliver my first child. To my disappointment I felt neither euphoric, nor any sense of hilarity. I simply felt a bit foggier, slightly ill, and thankful that this was not the only form of pain relief available to me!

9.3.2 Impacts

Despite the relatively low concentrations of nitrous oxide in the atmosphere, it is a very dangerous greenhouse gas. One kg of N_2O is estimated to cause the same level of warming over 100 years as 298 kg of carbon dioxide or 12kg of methane.

Moreover, it is now considered to be the single most important ozone depleting substance. This is not because it has a high impact on ozone depletion per molecule. Nitrous oxide's ozone depleting potential is relatively low – at only 0.017 where CFC-11 (the benchmark for ozone depleting substances) has an ODP of 1 and some chemicals have ODPs of over 10. However, the low ozone depletion potential is offset by the high quantity of nitrous oxide emissions and its long atmospheric lifetime compared to most ODPs.

N_2O also causes acid rain. Nitrous oxide reacts with water particles to produce nitric acid which has a pH between 4.1 and 5.1. Rain normally has a pH of approximately 5.6. Acid rain can harm plants and other species by dissolving important nutrients and minerals from the soil that are then carried away by the rain. Further, acid rain can lead to the release of toxic substances such as aluminium into soil.

9.4 An Indicator for Me-NO

As mentioned, the warming impacts of GHGs are often equated to an equivalent mass of CO_2 emissions (CO_2e) based on their Global Warming Potential. This indicator corresponds well to the relevant PB indicator – radiative forcing – which is essentially a measure of warming or cooling impacts. Thus, the proposed indicator for methane and nitrous oxide is the *net Me-NO emissions* measured in CO_2e.

9.5 The Limit

There are two Planetary Boundaries which correspond to both methane and nitrous oxide emissions:

- Radiative forcing ≤ ±1W/m^2
- Extinction Rate ≤ 10 E/MSY

There is a third that relates only to nitrous oxide emissions:

- Concentration of stratospheric ozone ≥ 290 (Dobson units)

It is not possible to derive a specific limit for Me-NO emissions from these PBs. Radiative forcing is a measure of the energy balance at the Earth's surface. It is an overall indicator of warming impacts of methane and nitrous oxide, warming impacts of other GHGs, warming or cooling impacts of changes to land reflectivity, and warming and cooling impacts of aerosols. There are many ways that limits for each of the forcings could be combined to achieve the limit of ≤ ±1W/m^2.

Me-NO emissions contribute to species extinction indirectly through their impacts on climate change. It is a reasonable assumption that provided the PB for radiative forcing is met, that climate change impacts of Me-NO emissions on species extinction rates are intrinsically managed.

Nitrous oxide is also an ozone depleting substance. This means that it reduces the amount of stratospheric ozone – a gas that forms a protective layer that filters ultraviolet radiation from the sun before it reaches Earth's surface. There is no specific limit proposed for nitrous oxide with respect to stratospheric ozone.

The International Panel for Climate Change (IPCC) representative concentration pathway (RCP)2.6 was introduced in Chapter 8. It is the most ambitious of four future emissions scenarios developed by the IPCC. This pathway shows end of century emissions for methane dropping to ≤143 Mt/yr and nitrous oxide to ≤5.3 MtN/yr (Prather et al., 2013). It then assumes constant emissions after 2100 (IPCC, 2013d) (IPCC, 2013a).

RCP2.6 was not used as the basis for the PQ for carbon dioxide because it was not sufficiently ambitious (see Chapter 7). The RCP2.6 targets for methane and nitrous oxide are even less ambitious than the target for carbon dioxide. However, the authors argue that this is because there is less potential for abatement of these gases from agriculture (van Vuuren et al., 2011).

The Me-NO targets in RCP2.6 are based on a reduction to almost zero energy related emissions of methane and zero process related emissions of nitrous oxide (van Vuuren et al., 2011). The remaining emissions shown are almost entirely from agriculture. Van Vuuren et al highlighted that there will increasingly be conflicting needs for land use, for reforestation, bioenergy carbon capture and storage (BECCS), food production, and biodiversity. They reason that the targets for methane and nitrous oxide are thus set on the basis of maximising food production per unit area.

9.5.1 RCP2.6 Targets and the PB for Radiative Forcing

It is not possible to derive limits for specific PQs from the PB for radiative forcing. However, it is possible to test proposed PQs against radiative forcing to confirm that the collective forcings do not exceed the limits. This is shown for the IPCC RCP2.6 values listed above.

The corresponding radiative forcings for the RCP2.6 targets for 2100 are (IPCC, 2013a):

- Methane ~ 0.27 W/m^2
- Nitrous oxide ~ 0.23 W/m^2

This gives a combined forcing for MeNO of approximately 0.5 W/m^2. To show that this is a reasonable proportion of the PB limit of ±1 W/m^2 forcings must also be estimated for the PQs for CO_2 (Chapter 8), forest land (Chapter 10), ozone (Chapter 11) and aerosols (Chapter 12). As many of these Quotas have not yet been introduced, the combined forcings of these Quotas and how they collectively respect the PB for radiative forcing is presented in Chapter 12.

The layer of ozone in the stratosphere filters harmful ultraviolet rays from the sun and protects life on Earth. In the mid-1970s scientists realised that some substances could, and were depleting the ozone layer (Chesick, 1975) (see Chapter 11).

The total ODP of nitrous oxide per year at the RCP2.6 target of ≤5.3 Mt N/yr would be 90,100 ODP tonnes (because the ODP of nitrous oxide is 0.017, see Section 9.3.2). There has already been a phase out amounting to 2.5 million ODP tonnes of ozone depleting substances since the Montreal Protocol was ratified (UN, 2016). Approximately 32,000 ODP tonnes remaining to be phased out. The RCP2.6 target of 5.3 MtN/yr for nitrous oxide is considered adequate to respect the PB for ozone on the following basis:

> The authors of the PB framework have indicated that provided the Montreal Protocol commitments are met, the PB for ozone depletion will be respected (Rockström et al., 2009a).
>
> The PB for stratospheric ozone has only been transgressed over Antarctica, and only in Austral spring. Current annual emissions of nitrous oxide are approximately 7.7 MtN/yr. There are a further 32,000 ODPt of Montreal Gases being emitted. This brings the total emissions of ODPs to approximately 162,900 ODPt. There is evidence that the ozone hole is currently repairing itself despite this residual level of emissions of ozone depleting substances (Strahan and Douglass, 2018). Thus, we are already tracking towards the PB for ozone even in Antarctica with current levels of OPS emissions greater than the proposed PQ levels including nitrous oxide emissions.

9.5.2 The Limit for Me-NO

On the basis that there are no proposals for more stringent limits for Me-NO emissions and that the RCP2.6 targets for Me-NO emissions in 2100 can be shown to sufficiently respect the corresponding PBs, these limits have been used for the PQ for Me-NO. Converting these limits to the control variable unit CO_2e (using global warming potential of 198 and 24 for nitrous oxide and methane respectively) and combing them gives a PQ of *net MeNO emissions* ≤5 $GtCO_2$e/yr.

9.6 Discussion

The global Me-NO footprint is approximately 11 $GtCO_2$e/yr (derived from (World Bank, 2009)), roughly twice the annual PQ for Me-NO. Table 15 shows examples of how this PQ could be put into practice at different scales of activity and across different sectors. The examples relate to varying timeframes.

Table 15: Examples of different scales of activity which have or could contribute to achieving the PQ for Me-NO emissions

Achieving the Planetary Quota for MeNO Emissions			
Large	Development of an independent global community to report on the scientific understanding of Me-NO emissions and corresponding impacts *e.g., the International Panel for Climate Change*	Develop a global treaty to limit Me-NO emissions *e.g. the Paris Agreement*	Develop innovative low/no Me-NO farming practices or solutions
Medium	Campaigns for low-Me-NO lifestyle choices: *e.g. Veganuary*	Legislate low-Me-NO farming practices	Develop plant-based meat alternatives *e.g., the Beyond Meat plant-based burger paties*
Small	Implement low Me-NO community projects *e.g. Develop an organic community vegetable garden*	Incentivise low Me-NO products *e.g. organic products*	Go fossil fuel free
Individual	Purchase low Me-NO products *e.g., fossil fuel electricity*	Drive local awareness around low Me-NO behaviours and practices	Educate the public about Me-NO emissions *e.g. Kip Andersen and Keegan Kuhn's documentary Cowspiracy*
	Community	**Government**	**Business**

9.7 Conclusions

Me-NO emissions are considered within a single Planetary Quota as they have similar impacts with respect to the Planetary Boundaries. The Planetary Quota for Me-NO is *net MeNO emissions* ≤5 $GtCO_2e$/yr. This is based on IPCC RCP2.6 targets for 2100.

CHAPTER 10

A Quota for Forestland

Abstract

Humans have been altering Earth's surface for more than 40,000 years. Deforestation and land-use change have occurred for much longer than many of the more "modern" impacts that have been occurring predominantly since the industrial revolution. All the same, land-use change has accelerated since the industrial revolution which has local and global impacts.

Forests play critical roles in the maintenance of the state of the Earth System. They are an integral part of the carbon, water, and nitrogen cycles. They provide important habitats. Moreover, they provide important resources for humans such as timber and food. The Planetary Boundary for land-use change is for forest area ≥75% of original forest area. Only 62% of original forest area is still forest now.

Forest area is critical to many of the Planetary Boundaries. The total area of global forest effects the Planetary Boundaries for land-use change, climate change, and biosphere integrity.

The Planetary Quota for forested land - *net reforestation* ≥11 Mha/yr. This can be compared with the net reforestation or deforestation associated with any scale of human activity. The limit is set in order to meet the Planetary Boundaries for land-use change, climate change, and biosphere integrity by the end of this century.

10.1 Introduction

Earth's surface is 510 million km^2. 71% of the surface is covered by oceans, leaving only 29%, or approximately 150 million km^2 of land. Of this land area, almost one third is classified as desert – defined as areas that have less total rainfall than evaporation over a year. Deserts have harsh conditions and are typically only very scarcely populated by living creatures or plants. This means that there are approximately 100 million km^2 available to support most terrestrial species, including humans.

In Chapter 7, critical pressures pertaining to the Planetary Boundaries (PBs) were assessed and grouped – where the pressures were found to be equivalent with respect to the PBs. Four of the pressures found relate to human use of land (seeTable 16). The first critical pressure, deforestation, is a type of land conversion – which is also a critical pressure. Deforestation is listed separately because of its particular importance with respect to the functioning of the Earth System and thus to the PBs. For the same reason, it has not been grouped under the same PQ indicator as the other critical pressures relating to land use, despite having the same set of corresponding PBs. The other land-use pressures are discussed in Chapter 16.

This chapter begins with a background of human manipulation and management of land and an overview of why forestland is of particular importance. This is followed by the case for the indicator selected and the scientific baseis for the proposed limit. The chapter concludes with a discussion about the PQ for reforestation in the context of today's deforestation practices.

Table 16: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicators, critical pressures, and corresponding PB indicators and limits which pertain to land use

PQ Indicator	Critical Pressures	Corresponding PB
Deforestation	Deforestation	Concentration of CO_2 in the atmosphere ≤ 350ppm,[a] Radiative forcing ≤ $1W/m^2$ Aerosol optical depth ≤ 0.1 Extinction rate ≤ 10 E/MSY[a] Remaining forest 75%
Percentage disappearing fraction (of species) (Chapter 16)	Land conversion Land segregation Land degradation	Radiative forcing ≤ $1W/m^2$ Aerosol optical depth ≤ 0.1 Extinction rate ≤ 10 E/MSY[b] Remaining forest 75%

Notes:

c. ppm – parts per million parts of atmosphere
d. E/MSY – extinct species per million species per year

10.2 Background

Intentional changes to natural landscape by humans can be traced back as far as 40,000 years to Australia. Fire is a natural part of the Australian landscape. Aboriginal people learnt to use it to their advantage. Nyungar people – aboriginals from the south-west of Western Australia - used "cool" and "hot" fires – fires of low and high intensity respectively – for different purposes. Cool fires were used to clear undergrowth for better access through dense bush, and to promote new growth; plant species with high nutritional value were the first to re-establish themselves after a cool burn. Cool fires were also used to promote the growth of grass. Fires were (and still are) used to maintain grazing habitats. "Hot" fires, which burn not only the undergrowth but also the middle and upper layers of forest or bush, were used to promote new grown of Wattan or Spearwood thickets. (Kelly, 1999).

Not all other cultures managed land-use changes to their advantage. Deforestation has been a primary cause of several societal collapses.

> When the first Polynesians arrived at Easter Island in approximately 800AD, it was covered in tropical forest, with huge palm trees, and dandelions as tall as trees. The island was home to the largest collection of breeding sea-birds in the Pacific. Over the years they cleared forestland for houses and gardens, and used timber for canoes, firewood, and to transport and lever into place their giant statues. By 1600 there were no trees left (see Figure 22). They had also hunted all but one of the sea-

birds to extinction. Without forest, they had no fruit, no timber for canoes to go fishing, no fuel for fires. Without the tree roots, the land eroded quickly, and agricultural yields dropped. The most widely available food remaining was themselves, and so they turned to cannibalism. The society collapsed. (Diamond, 2005)

The Anasazi collapse can also be attributed to deforestation. The Anasazi were Native-American people who were hugely advanced in many ways for their time. For example, they constructed buildings as high as 6 storeys with as many as 600 rooms beginning around 600AD. However, they did not have good forest-management practices. They cleared the forests close to their settlements, and then in a slightly broader radius, until the point that they were travelling 75 miles, to mountains 4,000 feet above their settlement for timber to use as fuel and construction materials. This timber all needed to be dragged back to the settlements by hand. The Anasazi survived several droughts by relocating their settlements, but in 1117, another drought occurred and there was no unexploited landscape left. This society collapsed two decades later. The environment remains void of trees. (Diamond, 2005)

From 27 BC the Roman Empire prospered for almost 500 years. Yet in 476, the last emperor was removed from power, and the Roman Empire collapsed. Deforestation is now believed to be one of the primary causes of this sudden collapse. Wood was an important resource used for building, heating, and for fire in industry. Wood was overharvested from some forest areas, while others were cleared entirely to make room for farmland to feed the rapidly growing population. Forests were also burnt down in response to native tribes who would escape into forests to launch surprise attacks. One of the greatest impacts of the deforestation was the loss of topsoil from hillsides to lowland areas. The hillsides were no longer productive and crop yields dropped. In addition, the lowlands formed marshes that were breeding areas for disease. In light of the lack of fuel, glass and brick industries relocated. The Roman Empire gradually weakened and was eventually overrun with barbarians. (Sing, 2001)

Figure 22: Easter Island Statues against a desolate backdrop void of trees ((Massardier, 1998) CC BY-SA 3.0[20])

The active management of forests, not including the controlled burning by Aboriginals, can be traced back as early as the 1400s to Venice. Wood was the essential foundation of all wealth at this time as without wood there were no ships, which meant no trade, defense, or power. The Venetian Great Council wrote laws to attempt to ensure adequate supplies of wood would be available for ship building (Mauch, 2013). However, these laws were targeted at reducing demand and not managing supply. For example, boat captains were charged fines for damaging oars. The laws were unsuccessful but give an interesting insight into the development of our understanding of forest systems. In the 1400s in Venice, there were already elaborate mapping and measuring methods in place. In the 16th century, time and not just space began to be incorporated into forest planning (Mauch, 2013). Silviculture – the practice of managing and maintaining forest systems – was first introduced in the 1700s by von Carlowitz (1713).

Despite these examples of our very early understanding of forest management and the importance of this, we are continuing to use forest resources faster than they can regenerate across the globe. Before the industrial era there were approximately 59 million km^2 of forest area. Today, there are less than 40 million km^2 remaining.

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Human impacts on forestland are not limited to chopping them down. Overhunting can lead to empty forest syndrome where ecosystems can collapse because of the lack of a key species. The demolition of relatively small areas of large forests for example to run roads through them can cause fragmentation – harming the forest function. Climate change has altered natural fire regimes that are fundamental to forest health. The introduction of alien species can damage forests. Air pollution can lead to acid rain which damages forests.

10.3 The Importance of Forests

More than half of the land surface area on Earth is classified as "arid". This includes cold regions (polar and tundra areas as well as high mountains and plateaus) which comprise 14% of the global land area. Drylands – including hyper-arid zones (true deserts), arid zones (less than 200mm annual rainfall), semiarid zones (seasonal rainfall regimes with max rainfall of 800mmm) and dry sub-humid zones (highly seasonal rainfall), comprise a further 47%. (Secretariat of the CBD, 2001)

Drylands are used for farming both crops and livestock. Grazing is a major use of global drylands. Drylands are at higher than normal risk of erosion. Poor management of non-desert drylands can and has led to desertification – almost 70% of global dryland area, 35 million km^2, is already affected by desertification (Secretariat of the CBD, 2001). Many dryland ecosystems sustain a degree of natural fire. However, human caused fires can still have impacts on the biodiversity of these ecosystems.

The non-desert surface area of Earth can be roughly categorized into forest, cropland, urban areas, and drylands. One of the key human pressures on biodiversity is habitat loss due to human activity, i.e., land-use change. Forests are the most important habitat. Approximately 80% of the world's terrestrial species are found in tropical rainforests and even localised deforestation can lead to the extinction of important species (WWF, 2014a). Forests also provide a lot of critical natural capital to humans, they are an important part of the carbon cycle, they are our supply for timber, paper, fuel, and other wood-based products.

Not all forests are equal. Tropical forests are the most diverse ecosystems on Earth. Forest plantations on the other hand, which cover more than one million km^2 of Earth's surface, are usually made up of a single tree species – frequently an introduced species. These forests are not a popular habitat and usually have low levels of biodiversity. There are management practices that can encourage species diversity. For the purpose of this thesis, forest area is defined as per the Kyoto definition (see Box 1).

Deforestation affects climate change in two key ways. It is responsible for as much as 17% of global emissions of carbon dioxide (IPCC, 2007). Deforestation also affects the reflectivity of Earth's surface. As much as -0.15 W/m^2 ±1 of radiative forcing (change in energy balance at Earth's surface) is attributed to changes in surface albedo.

Deforestation can also lead to aerosol pollution. Aerosols are small particles suspended in the atmosphere. They come from both natural and anthropogenic sources. One of the most common naturally-occurring aerosols is atmospheric dust particles. Deforestation can lead to erosion and eventually desertification. As more areas become desert, there is more loose sand and dust that can be carried into the atmosphere.

Box 10.1: Defining Forest

There is no singular definition for "forest area" that is widely accepted. The Convention on Biological Diversity (CBD) defines forests loosely as "ecosystems in which trees are the predominant life forms" (Secretariat of the CBD, 2001). The Food and Agriculture Organisation (FAO) of the United Nations defines a forest as "spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees being able to reach these thresholds in situ" (FAO, 2012). FAO do not include land that is predominantly used for agriculture or urban land as forest area. However, the CBD find the FAO definition very broad and suggest that a more rigorous definition for forest would be that of closed canopy forest. Yet even the definition for closed canopy forest ranges from thresholds of 30% to 70% canopy cover. The Kyoto definition is similar to the FAO definition but only requires10-30% of crown cover with the potential to meet 2-5 meters in height at maturity (UU, 1998). This definition continues, to clarify that forests can consist of closed formations or open forests. They include young forests which have not yet reached the required crown density, and temporarily unstocked forests (whether this is from human or natural causes) provided these are expected to revert to forests.

Defining forest is important. Some tree species such as the Australian native, Mallee, do not fit traditional European based definitions of forest, yet they withdraw carbon, prevent erosion, and provide natural habitat for local species. The Kyoto definition is the broadest of the formal definitions and as such is the definition used in this thesis.

10.4 An Indicator for Forestland

The original PB indicator for land-use change was the percentage of global ice-free land surface converted to cropland (Rockström et al., 2009a). This was updated in 2015 to be forest area ≥ 75% of original forest area (Steffen et al., 2015). 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 (Steffen et al., 2015).

As shown in Table 16, deforestation relates to four of the PB limits:

- Remaining forest 75%
- Extinction rate ≤ 10 E/MSY[a]
- Radiative forcing ≤ 1W/m^2
- Aerosol optical depth ≤ 0.1

Given that the area of forest needed (i.e., 75%) is more than the current area of forest (i.e., 62%), the limit for deforestation will be negative, thus implying a minimum rate of reforestation in units of hectares.

10.5 The Limit

It is difficult to determine baseline levels for forest area as human destruction of forest started approximately 10,000 years ago at the beginning of the Holocene over most of the world, and even earlier in Australia. It is thought that prior to the industrial era there were approximately 59 million km^2 of forest area. Before human influence it is estimated that about half of Earth's surface was forest or woodland – i.e., approximately 75 million km^2 (Secretariat of the CBD, 2006). Of the world's 15 billion ha of surface area, only 6.5 billion ha of this is suitable for forestry. This figure is taken to be the baseline figure for "original forest".

Table 17 shows estimates for minimum forest areas based on each of the PBs which corresponds with the pressure deforestation.

The minimum forest area needed to meet the PB for land-use change is roughly equal to the upper estimate for the forest area needed to meet the PB for the concentration of CO_2 in the atmosphere. As such, the PQ for reforestation is deforestation ≤ -11 Mha/yr. This can be compared to net deforestation of any scale of human activity.

Table 17: Summary of global deforestation limits based on different upstream PBs

Planetary Boundary	Minimum area to be reforested	Basis
Land-use change >75% original forest area restored	≤ -0.9 Gha or ≤ -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_2 concentration ≤ 350ppm	≤ -0.9 Gha or ≤ -11 Mha/yr	This would require reforestation between 0.6 (Watson et al., 2000) – 0.9 (Brown et al., 1996) billion ha by 2100. At the high end of this range this equates to total forest area of 4.9 billion ha.
Climate change: radiative forcing ≤ $1W/m^2$	NA	The PB for radiative forcing cannot be used to derive a minimum forest area. However radiative forcing impacts of deforestation and land-use change are discussed in Chapter 11.
Biosphere integrity: Extinction rate ≤ 10 E/MSY	NA	There is no specific global forest area 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% -99% (Fahrig, 2001, Wackernagel et al., 2002, The Brundtland Commission, 1987, Margules et al., 1988). There is a land-based PQ for biodiversity (see Chapter 15). As such, the limits pertaining to the PBs for land-use and climate change are considered adequate.

10.6 Discussion

From 2010 – 2015 the average rate of deforestation was 6.5 Mha/yr (FAO, 2016). To reverse this and achieve a reforestation rate of 11 Mha/yr will be challenging.

Table 18 lists examples of some of the different activities that could occur at different scales to help to make this transition.

Table 18: Examples of different scales of activity which have or could contribute to achieving the PQ for forestland

Achieving the Planetary Quota for Forestland			
Large	Develop global sustainable forestry standards	Develop a global treaty on forestry.	Reduce the footprint of business operations and reforest previously occupied land.

	e.g. the Forest Stewardship Council.		
Medium	Run tree planting community events	Legislate minimum national forest cover *e.g. Bhutan has a law that at least 60% of the country must be under forest cover.*	Innovate to incorporate increasing forest area in business practices *e.g. CapitaLand have built an office tower "Capita Green" in Singapore with 50 times greater volume of forest than the building footprint (i.e., the land area within the building perimeter) would have had as original forest area through innovative biophyllic design.*
Small	Community tree planting	Run tree planting community events	Only purchase sustainably sourced forestry products.
Individual	Plant trees		
	Community	**Government**	**Business**

10.7 Conclusions

Forest is the most critical land type for healthy Earth System functioning. This is because of its role in the climate system, and on the global water cycle, and becaue it provides important habitats to so many species.

Currently we are destroying forests at a rate of approximately 6.5Mha/yr. Only 62% of original forest remains. The Planetary Quota for forestland is *net deforestation* ≤ -11 Mha/yr. This can be compared to the net deforestation associated with any scale of human activity.

CHAPTER 11

A Quota for Ozone Depleting Substances

Abstract

A thin layer of ozone in the atmosphere protects humans and terrestrial life from harmful ultraviolet radiation. The human creation and emission of ozone depleting substances has thinned this layer so much that once a year a large localised region with almost no ozone appears over Antarctica. This is known as the hole in the ozone layer.

In 1989, a global treaty was put into place to ban the manufacture and use of substances which deplete the ozone layer, the Montreal Protocol. By 2009 the protocol had been ratified by every country. There has been a reduction of almost 98% in the use of ozone depleting substances. The ozone hole is starting to get smaller.

The hole in the ozone layer is an example of how human activity can alter global Earth System processes. It is also an example of how the global population can work together to begin to repair past environmental damage. It is thought that provided we respect the terms of the Montreal Protocol, the hole will repair itself before the end of this century. Thus, the Planetary Quota for ozone is zero emission of ozone depleting substances listed under the Montreal Protocol. Ozone depleting substances can be converted to a unit of “ozone depleting potential” tonnes. This unit can be used to compare emissions of Montreal gases of any scale of human activity to the Planetary Quota limit.

11.1 Introduction

The atmosphere is divided into five primary layers (Figure 23). Some of these layers have secondary layers within them. The troposphere is the layer closest to Earth's surface; the layer in which we live. The second lowest layer in the atmosphere is called the stratosphere. The stratosphere is more than 10km above Earth's surface (Fahey, 2003). At the bottom of the stratosphere is a very thin layer which contains relatively high concentrations of ozone (O_3), of up to 12 parts per million (ppm) (Fahey, 2003). This layer is called the ozone layer. The ozone layer is important as it protects life on Earth by filtering most of the ultraviolet radiation from the sun before it reaches Earth's surface.

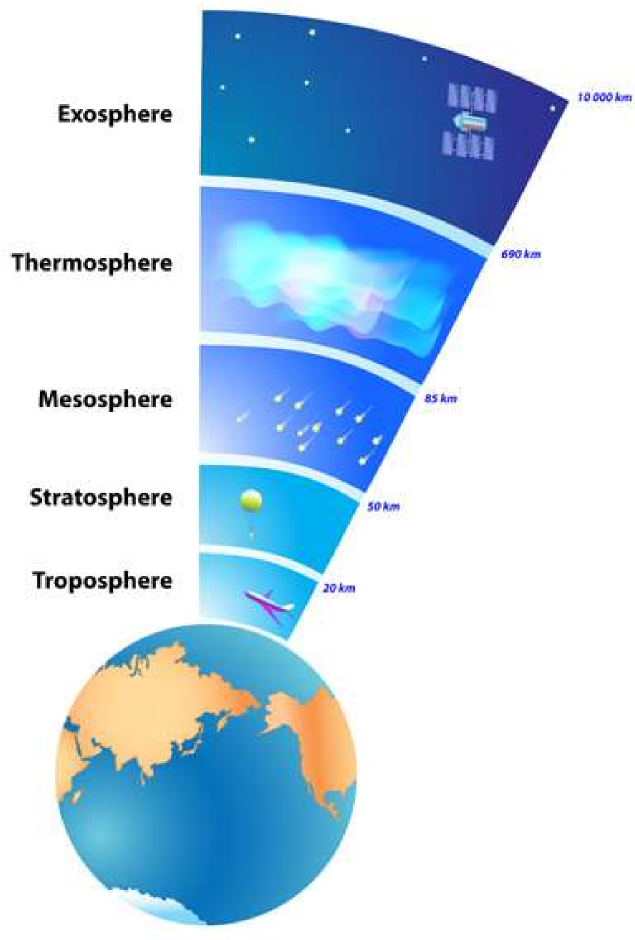

Figure 23: The five layers of the atmosphere ((unknown, 2015) CC BY-SA 4.0[21])

Human emissions of ozone depleting substances (ODSs), for example refrigerants such as CFCs, have reduced the concentration of ozone in the ozone layer. The thinning of ozone is

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large and localised over Antarctica. Each year, there is a period when there is almost no ozone in this area. This has been labelled the “hole” in the ozone layer.

The story of the hole in the ozone layer is one that conveys how large the consequences of human activity can be on the functioning of the Earth System. However, it can also be viewed as a success story, a way of showing how the global community can work together to successfully manage the Earth System and move away 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 ODSs (UNEP, 2017a). The ODSs included under the protocol are now known as “Montreal gases”. This phase out, which will not be complete until 2030, has already led to a decrease in the rate of ozone depletion over Antarctica (Strahan and Douglass, 2018). Some scientists estimate that the hole could be closed by 2050 e.g. (Solomon et al., 2016). Others predict that even by 2080 there may still be a small hole, but that we are making progress in the right direction (Strahan and Douglass, 2018).

Table 19 shows the critical pressures from Table 10 in Chapter 7 which have been grouped into a single Planetary Quota for ozone depleting substances. The corresponding Planetary Boundaries for these pressures are also shown. There is one critical ODS that is not shown in this table, nitrous oxide. The exclusion of nitrous oxide from this PQ is discussed later in this chapter.

Table 19: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicator, critical pressures, and corresponding PB indicators and limits

PQ Indicator	Critical Pressures	Corresponding PB
"Montreal gas" emissions (See Chapter 10)	Halocarbon emissions	Concentration of stratospheric ozone ≥ 290 (Dobson units) Radiative forcing ≤ ±1W/m^2 Extinction Rate ≤ 10 E/MSY[a]
	Hydrochlorofluorocarbon emissions	
	Halon emissions	
	Chlorofluorocarbon emissions	
	Carbon tetrachloride emissions	
	Methyl chloroform emissions	
	Hydrochlorofluorocarbon emissions	
	Methyl bromide emissions	
	Bromochloromethane emissions	
	Hydrobromofluorocarbon emissions	
	Hydrofluorocarbon emissions	

Notes:

a. E/MSY – extinct species per million species per year

The chapter begins with an overview of human influence on the ozone layer. This is followed by a discussion about the Montreal Protocol and an overview of how ODSs are currently being managed. The case for the PQ indicator and limit is then presented. Finally, the PQ is discussed in context of the status quo.

11.2 Background

Ozone (O_3), is a gas that occurs naturally in the atmosphere through ultraviolet sunlight reactions with oxygen molecules. The more sunlight, the more reactions, and so the ozone layer is thickest in the tropics (where it is most needed). When people claim that they can smell oncoming rain, this may well be the scent of ozone. Ozone is so smelly that it can be detected even in very low concentrations. Indeed, the name, ozone, comes from the Greek word – ozein – which means "to smell" (Fahey, 2003). Lightening can split nitrogen and oxygen which can lead the creation of ozone, so those down-wind of the lightening may well be able to smell that the storm is approaching.

There is very little ozone in the atmosphere. If all the ozone molecules were collected and distributed across Earth's surface, the layer of pure O_3 gas would be less than half a centimetre (Fahey, 2003). Ozone is measured in Dobson units (DU), a measure of the amount of a gas in a vertical column of atmosphere, with total ozone values varying between 200 and 500 (DU) across the globe. Ozone can be depleted naturally through reactions with naturally occurring chemicals. The total abundance of ozone at a given time is determined by the rate of production and the rate of depletion. (Fahey, 2003).

Approximately 90% of all atmospheric ozone is in the stratosphere (Fahey, 2003). Ozone protects life on Earth by filtering harmful wavelengths of Ultra Violet (UV) rays from the sun. There are three categories of UV radiation, UV-A, UV-B, and UV-C. UV-C is the most harmful. This is entirely screened out by dioxygen (for wavelengths less than 200nm) and ozone (for wavelengths above 200nm). UV-B radiation is less harmful than UV-A, but sill increases the risk of skin cancer, cataracts and the suppression of the immune system (Fahey, 2003). It can also harm plant life, single-cell organisms and marine organisms (Fahey, 2003). Most UV-B is filtered out by the ozone layer. UV-A radiation still reaches Earth's surface. It can still damage skin but it is far less harmful than shorter wavelength radiation (Fahey, 2003).

The remaining 10% of ozone in the atmosphere is located in the troposphere – the closest layer of the atmosphere to Earth's surface. Tropospheric ozone is a greenhouse gas. Ozone in the troposphere can reduce crop yields and forest growth. Humans exposed to ozone can have reduced lung capacity, chest pains, throat irritations and coughing, it can also worsen pre-existing heart and lung conditions (Fahey, 2003). Tropospheric ozone is naturally occurring and performs important functions such as the removal of methane, carbon monoxide, and nitrogen oxides. However, the increased levels from human activity have negative consequences. This is particularly true when increased concentrations of ozone are near humans, plants, and animals.

Ozone can be depleted by free radicals including nitric oxide, nitrous oxide, hydroxyl, chlorine, and bromine. Man-made compounds such as chlorofluorocarbons and bromofluorocarbons led to a substantial increase of chlorine and bromine in the atmosphere – the foundations of most ozone depleting substances. These increases in chlorine and bromine led to rapid depletion of stratospheric ozone. The hole in the ozone, where depletion has led to almost no ozone in a large localized area, is over Antarctica. This is in part because the ozone layer is thinner at the poles, and because the ozone depleting substances are predominantly released upwind of the Antarctic.

It was first recognised that some substances could deplete, and were depleting the ozone layer in the mid-1970s (Chesick, 1975). In 1985, an article was published in Nature confirming that there was a repeating springtime hole in the ozone layer (Farman et al., 1985). In response, the Montreal Protocol was developed.

11.2.1 Montreal Protocol

The Montreal Protocol is a global treaty put into place to manage human impacts on the ozone layer. It was first ratified in 1989 (UNEP, 2017a). By 2009 it became the first treaty to have universal ratification (UNEP, 2017b).

The Montreal protocol comprises a staged phase out of "Montreal Gases". There are different phase out dates for different gases and for countries of varying wealth. The gases included in the Montreal Protocol and their phase out dates are detailed inTable 20

.

Table 20: Montreal Gases - uses and phase out dates

Montreal Gas	Description	Phase Out
Halons	Any group of organohalogen compound containing bromine or fluorine and one or two carbons. They are predominantly used to extinguish fires – they were very useful because they do not conduct electricity and could thus be used to put out electrical fires.	Developed Countries 1993 Developing Countries 2010
Chlorofluorocarbons	These are most notable for their use to replace toxic refrigerants ammonia, methyl chloride, and sulfur dioxide which led to fatal incidents in the 1920s due to refrigerant leaks. CFCs were invented in 1928 by Thomas Midgley of general motors and in 1930 general motors and Du Pont formed a company to produce CFCs (called Freon) in large quantities. CFCs were also used in aerosol sprays, blowing agents for foams and packing materials, and as solvents.	Developed Countries 1995 Developing Countries 2010
Carbon tetrachloride	This was used to produce chlorofluorocarbon refrigerants. It was also used in lava lamps, by stamp collectors to reveal watermarks, as a solvent, a cleaning agent and in fire extinguishers. It was first made by Henri Victor Regnault in 1839.	Developed Countries 1995 Developing Countries 2010
Methyl chloroform	This was also developed by Henri Victor Regnault in 1840 and was used as a solvent.	Developed Countries 1995 Developing Countries 2015
Hydrobromofluorocarbons	These were used in Canada for experimental purposes but were identified as ozone depleting substances and phased out before they became produced or used commercially.	Developed Countries 1995 Developing Countries 1995
Methyl bromide	In 1999, an estimated 71,500 tonnes of synthetic methyl bromide were used annually worldwide (UNEP,	Developed Countries 2005 Developing Countries 2015

	1999). Almost all of this was for fumigation.	
Bromochloromethane	This was invented in Germany in the mid-1940s as a less toxic fire extinguisher to carbon tetrachloride.	Developed Countries 2002 Developing Countries 2002
Hydrochlorofluorcarbons	These are similar to CFCs but with less impact on the ozone layer – they have been used to replace CFCs as refrigerants. They are also used in insulative foams.	Developed Countries 2020 Developing Countries 2030
Hydrofluorocarbons	These are often used as refrigerants. They do not harm the ozone layer as much as the refrigerants they are replacing but they are a dangerous greenhouse gas. They are also used as blowing agents, extinguishers, cleaning products, and propellants. These substances were not originally included in the Montreal Protocol however on October 15th, 2016 an amendment was adopted to phase these down by more than 80%.	Developed Countries (85% Reduction) 2035 Developing Countries (80% reduction) 2045

11.2.1.1 The Kigali Amendment

Hydrofluorocarbons (HFCs) were developed in the 80s as a replacement to ozone depleting substances. It was later discovered that this substance is a very dangerous greenhouse gas with warming impacts thousands of times higher than CO_2 per unit of emission. Although the concern relating to this substance is for climate change rather than ozone depletion, the management of HFCs has fallen under the Montreal Protocol.

11.2.1.2 Nitrous Oxide

In the past, not much consideration was given to nitrous oxide's impacts on the ozone despite the knowledge that it is an ozone-depleting substance. The reason for this is the gas's relatively low ozone depletion potential (ODP). The ODP of a substance is a measure of the impacts of a kilogram of emissions with respect to ozone, compared to the impacts of CFC-11. CFC-11 is considered the benchmark gas with an ODP of 1. Some substances have much higher ODPs than CFC-11, for example, bromochlorodifluoromethane has an ODP of 7.9. Nitrous oxide has an ODP of 0.017.

Despite the low relative impacts of nitrous oxide, it has recently been brought under the spotlight as one of the most important ozone-depleting substances. This is because of its long atmospheric lifetime, and the high level of anthropogenic nitrous-oxide emissions. Nitrous oxide is not currently included under the Montreal Protocol.

The basis for the exclusion of nitrous oxide from the PQ for ozone is not its omission from the Montreal Protocol. The reason is that the limit for Montreal Gases – both for the Montreal Protocol and for the Planetary Quota – is zero.

Nitrous oxide is a naturally occurring by-product of agriculture. A limit of zero is not currently conceivable without putting an end to agriculture. To include it here would mean the limit for this PQ would have to be higher than zero. As such, nitrous oxide emissions are dealt with separately under the PQ for Me-NO. Chapter 9 shows that the impacts to the ozone layer from the proposed limit for nitrous oxide are unlikely to prevent the recovery of the ozone layer.

11.3 The PQ for Ozone

Ozone depleting potential of substances can be used to compare different quantities of emissions of each using the unit ODP kilograms. The PQ indicator for ozone is thus *emissions of Montreal gases* in ODPkg.

The Planetary Boundary for ozone depletion is ≤ 5% decrease in column ozone levels for any latitude with respect to 1964-1980 values (Chipperfield et al., 2006). It is difficult to equate this limit to an emissions budget. However, in the Planetary Boundaries publication Rockström et al. (2009a) state that the Montreal Protocol has put humanity on a path that will avoid the transgression of the PB for ozone, citing evidence of a decrease of 8-9% by 2005 of tropospheric concentrations of ozone-depleting gases from their peak values in 1992-1994 (Clerbaux et al., 2006).

The Montreal Protocol comprises a complete phase out of Montreal gasses other than HFCs by 2030. Current phase out of HFCs if for 80-85% phase out by 2035-2045, but there are also plans to halt all development of HFCs before this time. As such, the proposed PQ limit for emissions of Montreal Gases ≈ zero ODPkg.

The limit of zero means that the impacts of Montreal gases on the other PBs effected by Montreal gases (radiative forcing and extinction rate) are eliminated. The PQ for ozone depleting substances can be compared to the sum of ODP kilograms from all Montreal gases emitted for any scale of human activity.

11.4 Discussion

It is questionable whether a Planetary Boundary or Planetary Quota is needed for ozone depletion when we are already on the path to recovery. When I visited some of the authors of the PBs during my extended community engagement (see Chapter 7), not all agreed with its inclusion as a PB.

Ozone depletion is included in the Planetary Quotas for three reasons.

1. There is still a very large hole in the atmosphere that only continued and careful management will resolve.
2. The fundamental scientific basis of the Planetary Qutoas is the Planetary Boundaries. This thesis does not include any scientific assessment as to the validity or completeness of the framework. It would thus be incongruent with the project approach to exclude ozone depletion.
3. The purpose of the Planetary Accounting Framework (and thus the Quotas) is to provide a useful mechanism to promote change. The science of behaviour change suggests that humans need and want to see stories of success – that these can motivate humans into action (see Chapter 4). One of the greatest challenges to managing global problems is that people feel the problem is simply too big. The success story of the hole in the ozone and the Montreal Protocol is likely to be a useful tool in helping to generate confidence and action for change.

The journey to living within this PQ started several decades ago. However, we are not at the end of the path. Table 21 gives both examples of past actions and potential future actions that have or could occur to help humanity live within this PQ.

Table 21: Examples of different scales of activity which have or could contribute to achieving the PQ for Montreal gas emissions

Achieving the Planetary Quota for Montreal Gas Emissions			
Large	Develop global treaties to coordinate efforts to phase out ozone depleting problems: *e.g. the Montreal Protocol*	Join global initiatives to collaborate against global environmental problems: *e.g., the Montreal Protocol*	Innovate to provide solutions that allow communities to transition away from harmful activities *e.g., Alternatives to CFCs were developed in light of the Montreal Protocol*
Medium		Ban the sale of ozone depleting substances *e.g., most countries have now banned most ODPs.*	
Small	Lobby for global initiatives against environmental problems *e.g., Australian communities lobbied for ozone protection laws because of high rates of sunburn in children prior to the Montreal Protocol*	Run local campagns to educate the community about ozone depleting substances.	
Individual			
	Community	**Government**	**Business**

11.5 Conclusions

Ozone depleting substances are already being phased out under the Montreal Protocol. This phase out is considered sufficient to meet the Planetary Boundary for ozone depletion.

The Planetary Quota for emissions of OPDs is *emissions of Montreal gasses* ≈ zero ODPkg. This limit can be compared to the sum of ODPkg of Montreal gasses emitted during any scale of human activity. We are on track to achieve this PQ. As such, it can be used as a success story to motivate action towards living within the other PBs.

CHAPTER 12

A Quota for Aerosols

Abstract

Aerosols are small particles suspended in the atmosphere. They can absorb and scatter light and change cloud formations. They have both warming and cooling impacts but, overall, the impacts are cooling. They dampen the warming impacts of fossil fuel emissions. However, they can be very harmful to human health.

Until now there has not been an indicator that could link human activity to the abundance of aerosols in the atmosphere. This is because the pathways from the emission of aerosols and precursor gases to aerosols vary greatly and are influenced by several environmental factors such as temperature, humidity, and air movement. However, without a way to even approximate this relationship, it is difficult to effectively manage or limit the source of the emissions.

A new indicator is thus proposed to link the emission of aerosols and precursor gases to aerosol abundance. It is a measure of the equivalent aerosol abundance if emissions occurred at a global scale, in the unit *aerosol optical depth equivalent*.

The new indicator is not intended to estimate the local state of the environment after emissions. Rather, the intent is that the emissions related to an activity can be compared to another activity, and to scientific limits at local and global scales.

The Planetary Quota for aerosols is *aerosol optical depth equivalent* between 0.04 – 0.1. This can be compared to the "aerosol footprint" of any scale of human activity. The limit is set on the basis of balancing the need to retain some cooling effects to offset global warming, as well as the need for clean air for the health of humans and other species.

12.1 Introduction

The term *aerosols* describes 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 they can develop from the emission of precursor gases. The main anthropogenic sources of aerosols are dust (due to desertification), and emissions of sulphur oxides, nitrogen oxides, dimethyl sulphide, organic carbon, black carbon, and volatile organic compounds (Boucher et al., 2013). Atmospheric aerosol loading was included as a Planetary Boundary (PB) because of the influence of aerosols on the climate system through changes to radiative forcing (predominantly cooling), and impacts on human health through air pollution (Rockström et al., 2009b). Air pollution has been identified by the World Health Organisation (WHO) as the single greatest risk for global health (WHO, 2016).

Table 22 shows the critical pressures that have been included in the Planetary Quota (PQ) for aerosols. Deforestation is not included in this list because it is cannot be measured in a similar way to the other pressures. There is a specific PQ for forestland (see Chapter 10).

Table 22: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicator, critical pressures, and corresponding PB indicators and limits

PQ Indicator	Critical Pressures	Corresponding PB
Aerosol and precursor emissions	Carbon monoxide emissions	Radiative forcing ≤ ± 1W/m^2 Aerosol optical depth ≤ 0.1 Extinction rate ≤ 10 E/MSY[a]
	Non-methane volatile organic compounds	
	Nitrate emissions	
	Sulphate emissions	
	Black carbon emissions	
	Organic carbon emissions	

Notes:

a. E/MSY – extinct species per million species per year

This chapter begins with a background about aerosols and how these are currently measured. There is no existing indicator which can be used to measure the collective impacts of aerosol and precursor gas emissions. As such, the chapter goes on to introduce the new indicator developed for this purpose – the *aerosol optical depth equivalent.* This is followed by the scientific basis for the proposed Planetary Quota for aerosols. The chapter concludes with a discussion of this PQ in the context of the status quo, including some examples of activities that could help us to live within this PQ.

12.2 Background

Atmospheric aerosols are suspended solid or liquid particles in the air with diameters ranging from a few nanometres to a few tens of micrometres. Aerosols absorb and scatter solar radiation and affect cloud formation. They have both warming and cooling effects on the global climate, but the net effect is cooling.

<u>Box 12.1: Aerosol Cans</u>

There is common confusion or misconception concerning the environmental impacts of aerosol spray cans.

Aerosol spray cans are named as such because they use high pressure to emit small droplets (aerosols) of liquid. Unlike the aerosols of concern in this section, these aerosols from spray cans do not normally stay suspended in the atmosphere but rather fall to the surface over which they were sprayed. The environmental impacts of aerosol cans are not (usually) related to the aerosols produced but rather due to the compressed gases used to propel the aerosols.

Prior to the Montreal Protocol, aerosol spray cans often used ozone depleting substances (see Chapter 11) as the propellants. There were widespread campaigns against the use of these cans because of to their contribution to the hole in the ozone layer. Now, most of the ozone depleting gases previously used in these cans have been phased out and most now use alternative gases that do not contribute to depletion of the ozone layer.

The idea that aerosols could change global climate dynamics was brought to light in the 1940s when some scientists were concerned that their presence might fast track the Earth System into another ice age e.g., (Rasool and Schneider, 1971, Bryson, 2009) (see Chapter 2). As scientific understanding of the relative impacts of greenhouse gases and aerosols advanced, it became apparent that the warming impacts of fossil fuels would substantially outweigh the cooling impacts of aerosols. However, the cooling effects of aerosols have substantially masked the warming effects of greenhouse gases; without aerosols the world would be substantially warmer (Boucher et al., 2013).

Aerosols influence the climate system in a complex way. They both scatter and absorb radiation (considered the “direct effects”) and modify amounts and properties (microphysical and radiative) of clouds (the "indirect effects") (Chin, 2009). Aerosols can both warm and cool Earth's surface, but on average they provide a cooling effect (Boucher et al., 2013). They can be visible as dust, smoke and haze, but can also be invisible to the human eye. Most aerosols come from natural sources such as sea salt and dust. However, human activity is increasing the concentration of aerosols in the atmosphere through the direct emission of aerosols, the emission of precursor gases that result in aerosol formation, and through land use that results in desertification and therefore increased atmospheric dust. Concerns over aerosols in the atmosphere are distinct from past concerns regarding the use of aerosol cans which is an ozone rather than an aerosol problem (see Box 12.1).

Many aerosols affect human health including nitrous oxides, ozone, carbon monoxide, and sulphur dioxides. Air pollution has been identified by the World Health Organisation as the single greatest risk for global health (WHO, 2016). 5% of all deaths in 2012 were solely attributable to air pollution (WHO, 2016). In 2016, 92% of the world's population lived in areas that are outside the World Health Organisation ambient air quality recommendations (WHO, 2016).

12.3 Measuring Aerosols

The concentration of aerosols in the atmosphere can be quantified using an optical measure (i.e., the amount of light which can pass through the atmosphere), or by mass concentration (i.e., the mass of aerosols per volume of atmosphere):

- Aerosol Optical Depth (AOD) – also known as Aerosol Optical Thickness is the former. It is a dimensionless unit that expresses the fraction of incident light either scattered or absorbed by airborne particles in a vertical column of air (Chin, 2009). An AOD value of zero indicates completely clear skies. An AOD of one indicates that no light can permeate the atmosphere (Chin, 2009). The Planetary Boundary for aerosol loading is a maximum regional AOD of 0.25 – with an increase due to human activity ≤ 0.1 (Steffen et al., 2015). The global mean value at 550nm is approximately 0.12 – 0.16 (Chin et al., 2014).
- Particulate Matter Concentration (PMC) is a mass concentration measure of aerosols. It is a measure of the number of grams of particulate per volume of air ($\mu g/m^3$). PMC is often reported for particulate matter of a specific size, commonly with diameters less than 2.5µm and 10µm ($PM_{2.5}$ and PM_{10}). $PM_{2.5}$ is the most harmful category of aerosol with respect to human health (Fantke et al., 2015). For this reason it is often used as a proxy indicator for air pollution (WHO, 2016).

The World Health Organisation uses the metrics $PM_{2.5}$ and PM_{10} to communicate guidelines for minimum air quality standards (see Table 23). These guidelines are for maximum particulate concentration. The WHO position is that there is no level of particulate matter that does not have any impacts on human health. They therefore recommend that target levels are as low as possible (WHO, 2016).

Table 23: World Health Organisation Guidelines for Ambient Air Quality

	$PM_{2.5}$	**PM_{10}**
Annual mean	10 μg/m^3	20 μ/m^3
24-hour mean	25 μg/m^3	50 μg/m^3

These units both pertain to the *state* of the environment. Until now, there has not been an indicator with which to collectively measure aerosols at a *pressure* level in a way that can be scaled.[22]

Fantke et al. (2015) identified the importance of assessing $PM_{2.5}$ health impacts in environmental impact assessments. They chose $PM_{2.5}$ because this has the most severe impacts on human health (Harrison and Yin, 2000, Lim et al., 2012, Lippmann and Chen, 2009). They developed a framework to include the health impacts of $PM_{2.5.}$ into life cycle assessment. Their framework considers the amount of primary and secondary particulate matter that is taken in by people. An exposure response factor and a severity factor are then applied to determine a human health related impact score in the health unit *disability-adjusted life years* (DALY).

Fantke et al.'s (2015) framework is extremely useful. It provides a quantitative measure of human health impacts from various activities. However, as is the problem with any life-cycle-assessment indicator, there is no clear limit. How many DALYs are acceptable for a given product? It is also specific to the location of the emissions. The intake fraction of $PM_{2.5}$ will vary greatly depending on population density, proximity to the activity, and local climate (Humbert et al., 2011). Poor air quality is a local problem. It is also a global problem. Aerosols in the atmosphere are affecting the climate system. Air quality affects humanity directly through health impacts, and indirectly through impacts on Earth-system functioning. Fantke et al.'s framework has strong local relevance. It was developed with a focus on health, not

[22] A *pressure level* means at the level of environmental flows, i.e., the emission of aerosols and precursor gases. See Chapter 5 for a description of different categories of environmental indicators including states and pressures.

on global Earth System impacts. It is not straight forward to relate it to the Planetary Boundary for aerosols. Nor could it easily be scaled and adapted for use in a poly-scalar approach.

(Gronlund et al., 2015) also look at assessing the human impacts of $PM_{2.5}$ through a characterisation factor – impact per kg of $PM_{2.5}$ emitted. Their approach has similar health approach and thus similar limitations to Fantke et al.'s.

In a study linking life-cycle-impact assessment to the Planetary Boundaries, Ryberg et al. (2018) proposed characterisation factors (CFs) to link key environmental flows to Planetary Boundaries. Their work includes characterisation factors linking emissions of key aerosols and precursor gases to AOD, in kilograms per year. The CFs are estimated at global and regional levels and express a change in AOD per annual mass of aerosol emissions. These CFs thus link the pressure of aerosol and precursor emissions at a regional scale to the *state* of aerosols in the atmosphere (aerosol optical depth).

12.4 Equivalent Aerosol Optical Depth

The pathways from the emission of an aerosol or a precursor gas are complex. The pathways vary with local environmental conditions. Aerosols and precursor gases also interact with one another. This makes it prohibitively difficult to accurately estimate the impacts of the emissions of a given substance to local AOD levels or to PMC without complex computer modelling.

The CFs proposed by Ryberg et al. (2018) are based on very simplified calculations. The atmospheric transport of aerosols is perhaps not adequately captured. However, the complexity of interactions between different aerosols and the lifetimes of different aerosols and precursors is considered, albeit simplified. It would be highly inaccurate to suggest that using these calculations one could predict the resulting AOD.

However, the framework has substantial merit in that it links the *pressure* of aerosol and precursor emissions to a *state*. Building on their approach it is possible to estimate the contribution of an activity to global average AOD. This should not be confused with an estimation of actual change in AOD. Such an estimation would be highly inaccurate because of variations to local conditions and the interactions between different aerosols and precursors. However, by equating emissions to impacts on the global average, one can effectively estimate the equivalent impacts of emissions, or, equivalent AOD (AODe).

This concept is not dissimilar to the way we currently measure greenhouse gases or ozone depleting substances. Greenhouse gas emissions can be assessed for their global warming impacts by equating them to an amount of carbon dioxide (CO_2) that would warm the atmosphere by the same amount – the *equivalent* CO_2 (CO_2e). In the same vein, the ozone depleting potential (ODP) of ozone depleting substances is measured with respect to a benchmark gas. Emitting 1kg of nitrous oxide, with an ODP of 0.17, is equivalent to emitting 0.17 kg of CFC-11 – the benchmark gas. The premise of AODe differs slightly from the examples given in that the equivalency is not set against a substance but against an effect, i.e., change in AOD. However, the basis of the unit is of similar origin to CO_2e and ODP.

12.4.1 Calculating AODe

AOD can be calculated using the formula:

$$AOD = MEE\ x\ M \qquad \text{Eq. 1}$$

MEE is the mass extinction efficiency or specific extinction in m^2/g and M is the aerosol mass loading per unit surface area in g/m^2.

The CFs developed by Ryberg et al. (2018) are based on the derivation of aerosol mass loading for a given activity multiplied by the specific extinction (at a certain relative humidity) derived from Chin et al. (2002). Mass loading for a given substance (n) is estimated using Equation 2, where E denotes average emissions in kg/yr, τ denotes residence time in years, and A denotes global (or regional) terrestrial area in m^2.

$$M_n = E_n \times \frac{\tau_n}{A} \qquad \text{Eq. 2}$$

The CF is then given by Equation 3 where β denotes the specific extinction efficiency.

$$CF_n = \beta_n \times M_n \qquad \text{Eq. 3}$$

Building on this approach, Ryberg and Meyer have derived an alternative method to estimate AODe.[23] The mass loading for AODe is calculated using Equation 4, where A(x) represents corresponding area. For example, if estimating the AODe for an individual, A(x) could be a per capita share of global terrestrial area.[24]

$$M_n = E_n \times \frac{\tau_n}{A_x} \qquad \text{Eq. 4}$$

[23] Manuscript in preparation
[24] Determining the appropriate area will depend on the allocation procedure selected for downscaling the global quotas. See Chapter 16 for more on allocation procedures.

The resultant AODe for substance n is then determined using Equation 5, and total AODe from an annual emission flux using Equation 6.

$$AODe_n = \beta_n \times M_n \qquad \text{Eq. 5}$$

$$AODe_{steady\ state} = \sum AODe_n \qquad \text{Eq. 6}$$

12.5 The Limit

There are three Planetary Boundaries that correspond with this Planetary Quota (see Table 22):

- Aerosol optical depth ≤ 0.1
- Radiative forcing ≤ ± 1 W/m^2
- Extinction rate ≤ 10 E/MSY[a]

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) ≤ 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} ≤ 0.1 (Steffen et al., 2015). This limit was set on the basis of limiting impacts on the ocean-atmospheric circulation (Steffen et al., 2015).

As discussed in Chapter 9, it is not possible to derive a specific limit for radiative forcing for different forcing elements from the PB for radiative forcing. However, based on the Planetary Quotas determined for carbon dioxide (Chapter 8), methane and nitrous oxide (Chapter 9), forestland (Chapter 10), and ozone depleting substances (Chapter 11), a range of acceptable radiative forcing levels from the PQ for aerosols can be determined.

There are also no specific air quality guidelines pertaining to species extinctions. However, as discussed in Section 12.3, $PM_{2.5}$ is often used as a proxy for air quality. The WHO guideline for human health is $PM_{2.5}$ ≤ 10μg/m^3. This limit is assumed to be an acceptable proxy limit for other species.

There have been studies linking AOD to both radiative forcing e.g. (Hansen et al., 2005, Andersson et al., 2015) and to $PM_{2.5}$ e.g. (Engel-Cox et al., 2004, Liu et al., 2004, Gupta and Christopher, 2009, Gupta et al., 2006, Gupta et al., 2013, van Donkelaar et al., 2010).

12.5.1 Radiative Forcing

The radiative forcing from the PQs for carbon dioxide (Chapter 8), methane and nitrous oxide (Chapter 9), forestland (Chapter 10), and ozone depleting substances (Chapter 11), are shown below.

Carbon Dioxide

The radiative forcing for a given atmospheric concentration of CO_2 can be calculated using Equation 7 (Ramaswamy et al., 2001).

$$\Delta F = \alpha \ln(\frac{C}{Co}) \qquad \text{Eq. 7}$$

Where α = 5.35, C is the atmospheric concentration of CO_2 in ppm, and C_o is the base level concentration of CO_2 (278ppm in 1750). This gives a CO_2 forcing for 350ppm of 1.23W/m^2.

Methane and Nitrous Oxide

The corresponding radiative forcings for the PQs for methane and nitrous oxide are (IPCC, 2013a):

- Methane ~ 0.27 W/m^2
- Nitrous oxide ~ 0.23 W/m^2

This gives a combined forcing for MeNO of approximately 0.5 W/m^2.

Other Greenhouse Gases

HFCs, PFCs, and SF_6 were excluded from the list of critical pressures because they currently each contribute less than 1% towards total radiative forcing. However, in future, their relative contribution could be much higher. Indicative radiative forcing values for these are based on RCP2.6 projections for 2100 to give 0.142W/m^2 (HFCs – 0.126W/m^2 and PFCs and SF_6 combined of 0.016W/m^2) (IPCC, 2013a).

Forestland

It is not straightforward to predict the future albedo (surface reflectivity) of the Earth. To meet the PB for land-use would require approximately 1billion hectares of reforestation. However, it is difficult to estimate the areas of ice, albedo of future urban areas, total future cropland areas etc. The change in land use since 1870 lead to a change in albedo with a radiative forcing impact estimated at -0.15 ± 0.1 W/m^2 (Myhre et al., 2013a). Major reforestation would reduce the albedo and therefore have a positive forcing effect. To determine a rough approximation for future albedo forcing, it is assumed that this will be of a similar order of magnitude as changes since 1870, but in the opposite direction. Thus, the estimated radiative forcing based on the increase in forest land is approximately 0.15W/m^2.

Ozone

The PQ for ozone is zero. As such, the forcing is also zero.

Combining the estimated forcings above gives a total (excluding aerosol impacts) of $2.25W/m^2$. This means that to respect the PB for radiative forcing of ≤ ± $1W/m^2$, the radiative forcing impacts of aerosols would need to be ≤ $-1.25W/m^2$ (to a minimum of -3.25).

Radiative forcing due to stratospheric aerosols depends predominantly on the aerosol optical depth. The adjusted forcing due to aerosols can be approximated using Equation 8 (Andersson et al., 2015, 1993, Hansen et al., 2005).

$$-25 \times AOD \approx RF_{Aero} \qquad \text{Eq. 8}$$

Thus, to respect the PB for radiative forcing, the PQ for aerosols must be 0.04 ≤ AODe ≤ 0.13.

12.5.2 Air Pollution

There have been several studies looking at the relationship between AOD and $PM_{2.5}$ including (Engel-Cox et al., 2004, Gupta et al., 2013, van Donkelaar et al., 2010, Gupta et al., 2006, Liu et al., 2004). The simplest relationships are given by a two-variable regression equation. AOD values obtained using the WHO $PM_{2.5}$ recommendation for annual concentration limits of 10µg in a sample of two-variable regressions listed in (Gupta et al., 2013) gives results as shown in

Table 24.

Table 24: AOD values according to various two-variable regression equations

Formula	AOD	Reference
$PM_{2.5} = 7.54 + 18.66AOD$	0.14	(Engel-Cox et al., 2004)
$PM_{2.5} = 87.5AOD$	0.114	Derived by (Gupta et al., 2013) from (van Donkelaar et al., 2010)
$AOD = 0.006 \times PM_{2.5} + 0.149$	0.209	(Gupta et al., 2006)
$PM_{2.5} = 81AOD$	0.123	(Liu et al., 2004)

The highest value in this range is based on the relationship proposed by Gupta et al. (2006). The same author later derived an alternative formula (see

Table 24, line 2) which gives much more congruent results with the other equations. This later proposal by Gupta suggests a change or advance in thinking, as such, his earlier proposal can be discounted.

All of the calculations indicate that a limit based directly on the PB limit (i.e., AODe ≤ 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. (Gupta et al., 2013, Engel-Cox et al., 2004, NOAA).

12.5.3 The PQ for aerosols

Considered in isolation, the lower AODe the better. 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 (Boucher et al., 2013).

Thus, the PQ for aerosols comprises both a minimum to offset radiative forcing impacts and a maximum to limit impacts on human health. This gives a PQ for aerosols of 0.04 ≤ AODe ≤ 0.1. This can be compared with the “aerosol footprint” of any scale of human activity – i.e., the annual AODe associated with the activity.

The argument could be made that further GHG reductions and increased reforestation would allow the PQ for aerosols to be lowered further. However, the current PQs for GHGs and reforestation are extremely ambitious. Given that the PB for aerosols and the WHO health guidelines can be met with the proposed PQ for aerosols, it does not seem worthwhile to push the PQs for GHGs and reforestation further at this stage.

12.6 Discussion

There is no data on current AODe. Estimates of global mean AOD values of 0.12 – 0.16 (Chin et al., 2014) do not distinguish human induced aerosols from naturally occurring aerosols. However, given these global mean values, we can deduce that we have not exceeded the PQ for aerosols at a global scale. Regional AODe is likely to be above the PQ level for many industrial and/or highly populated locations.

Table 4 lists examples of activities for different scales of activity across different sectors which either have already or could in future contribute towards managing human activity within the PQ for aerosols.

Table 25: Examples of different scales of activity which have or could contribute to achieving the PQ for aerosols

Achieving the Planetary Quota for Aerosol and Precursor Emissions			
Large	Develop guidelines for minimum healthy air quality *e.g., The WHO minimum standards for clean air.*	Set minimum air quality laws and implement initiatives to manage polluters *e.g. German laws on Air Quality Control limit emissions of relevant air pollutants in new installations and require that existing installations must be upgraded.*	Improve business practices to reduce and eventually eliminate the emission of aerosols and pre-cursor gases
Medium	Install a community renewable energy plant	Manage local air quality *e.g. Stuttgart local government reduces public transport fares to half rates when air pollution levels exceed a certain level to encourage citizens out of cars.*	
Small	Transition to fossil fuel free power	Educate communities about how to make choices for better air quality	
Individual	Walk or train instead of driving		Develop technology to reduce reliance on aerosol and precursor gas emitting products and services *e.g. Elon Musk and Tesla*
	Community	**Government**	**Business**

12.7 Conclusions

Aerosols suspended in the atmosphere are harmful to human health and are affecting the global climate. There was not previously an indicator that collectively measured the emissions of aerosols and precursors in a way that could be applied to different scales of activity.

This chapter introduced the new metric AODe, a measure of the relative impacts of aerosols and precursors on the atmospheric aerosol depth. The Planetary Quota for aerosols is $0.04 \leq AODe \leq 0.1$. The upper limit is set to minimise impacts of aerosols on human health. The lower limit is to continue to offset warming impacts from other forcing agents.

CHAPTER 13

A Quota for Water

Abstract

Water is a unique resource in that it is essential to life and irreplaceable. The water cycle is a critical Earth System process that human activity is beginning to alter. Water availability varies significantly across the globe. There is an abundance of water in some places, and extreme shortages in others. This regionality has led to some debate as to the existence of a global limit for water.

The regional variability of water scarcity does not mean that water is not a global commodity. Water used directly by a consumer is only a small proportion of her total water use. Water is also used indirectly in the production of goods and services as "virtual water". Approximately 40% of the water consumed in Europe is virtual water. It is not a rational argument to suggest that those in water rich locations need not be concerned about water consumption as much of the water they consume is likely to be from other locations.

The Planetary Boundary for water is only for blue water, i.e., it excludes the use of green water (rainwater) and grey water (contaminated water). Blue water consumption is a reasonable proxy indicator with which to understand the state of the world's water assets. However, the Planetary Quota for water needs to be in a unit that makes sense across different scales of human activity. As such, the use of green water and production of grey water are both relevant and important. Further, the Planetary Boundary for water considers gross water consumption. The level of water treatment now available is such that net water consumption is substantially lower than gross water consumption. It is also more relevant to planetary health.

There is no consensus as to a global water budget for net blue, green, and grey water. However, some argue that even at current consumption rates many of our global water bodies are under stress suggesting that the upper limit cannot be higher than current consumption rates.

Thus, the Planetary Quota for water is net water (blue, green, and grey water) ≤8,500km^3. This limit is set based on the current global water footprint and can be compared to the water footprint of any scale of activity.

13.1 Introduction

Water is a unique resource as there are no substitutes for most of its uses (Postel et al., 1996). It is impractical to transport it further than a few hundred km in its virgin form, although the transportation of embodied water in food and products is commonplace. The total amount of water on the planet doesn't change. However, humans can impact both the accessibility and the quality of water.

Table 26 shows the critical pressures which have been grouped for the Planetary Quota (PQ) for water, and the corresponding Planetary Boundaries. It is not only the consumption of water that is addressed through this PQ but also the contamination of water.

Table 26: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicator, critical pressures, and corresponding PB indicators and limits

<table>
<tr><th>PQ Indicator</th><th>Critical Pressures</th><th>Corresponding PB</th></tr>
<tr><td rowspan="3">Water use</td><td>Water consumption</td><td>Water consumption ≤ 4,000km^3</td></tr>
<tr><td>Use of chemicals</td><td rowspan="2">(Novel entities)[a]
Water consumption ≤ 4,000km^3</td></tr>
<tr><td>Disposal of chemicals</td></tr>
</table>

Notes:

b. There is no indicator or limit for the PB for novel entities

This chapter begins with an overview of the water cycle and an explanation of the different categories of water (green, blue, and grey). This is followed by the justification for a global water boundary. The main body of the chapter is dedicated to presenting the case for the water indicator selected and the corresponding limit. The chapter concludes with a discussion about what the PQ for water could mean in practice for society today.

13.2 Background

Fresh water is essential to human survival. Not only because we need to drink it, but also because it is needed to produce food. Approximately 90% of water used by humans is used for agriculture. Inland fisheries are critical sources of nutrition – particularly in land locked countries. Humans also use water as a source of power, for hygiene, and for recreational purposes.

When viewed from outer space, it seems that Earth is abundant with water. Over 70% of Earth's surface is water. However, 97.5% of the world's water is saline. Of the remaining 2.5%, some 35 million km^3 of fresh water, approximately 24 million km^3 (69%) is frozen (Postel et al., 1996). This leaves approximately 11 million km^3 of fresh water which is located in aquifers, soil pores, lakes, swamps, rivers, plant life and the atmosphere (Secretariat of the CBD, 2001, Shiklomanov, 1993)

Water can be divided into renewable and “fossil” water. Renewable water is water that flows through the solar-powered hydrological cycle i.e., from the atmosphere, to rain water, then water stored in rivers and lakes and some groundwater aquifers. This water has a mean residence time in each state of approximately 2.5 weeks (Oki and Kanae, 2006). The term fossil water refers to water which has been stored underground, undisturbed for millennia. It can be tapped; however, recharge takes hundreds or thousands of years (Postel et al., 1996). Accessing this water is thus depleting reserves and can be likened to our depletion of oil wells.

Salt water can be turned into freshwater through a process called desalination. 0.1% of the world’s water supply in 1990 was desalinated water (Wangnick Consulting, 1990). The problem with desalination is that it is energy intensive. The theoretical minimum energy needed is just under 1 kWh/m^3 of water (Postel et al., 1996). Current best practice is between 2.5-3.5 kWh/m^3 (AMTA, 2016).

There are several different ways to talk about water. Fresh water is either referred to as green water or blue water. There are also two other categories of water, grey water and virtual water.

> Green water is precipitation on land which does not run off or recharge ground water.
>
> Blue water is fresh surface water and groundwater, i.e., the water found in freshwater lakes, rivers and aquifers.
>
> The grey water footprint is the amount of water that would be needed to dilute pollutants in water to meet specific water standards. (Mekonnen and Hoekstra, 2011b). The term grey water is also used to describe waste water from sinks and showers (as opposed to waste water from kitchens and toilets which is known as black water). This is not the same as the grey water footprint.
>
> Virtual water is the term used to describe the water that is used in the production and transportation of goods and services but is not actually contained in the final product. For example, a lot of water is needed during the extraction of coal from coal mines. The coal will then be transported to a power plant, which also uses water in

the generation of electricity. This water is not delivered as water to homes but was fundamental in producing the electricity. It is thus considered the virtual water.

Three key risks have been identified regarding human manipulation of the water cycle (Rockström et al., 2009a):

1. Water consumption that alters volumes and flow patterns of water bodies;
2. Loss of soil moisture; and
3. Decline in moisutre feedback of vapour flows.

The first risk is about over-appropriation of blue water. The second two pertain to the disruption of the green water cycle.

Water bodies decline and are replenished naturally. They can feed and be fed by rivers and streams. Rain can replenish water bodies and evaporation can reduce them. If humans withdraw water at a rate higher than the natural cycle can replenish, water bodies can begin to dry up (see Box 13.1). This might mean habitat loss for aquatic ecosystems, diminished water supply for downstream needs, or a threat to water availability for ongoing human consumption.

Loss of soil moisture occurs through land-use change. Tree and shrub roots allow soil to hold water and release it through evapotranspiration. Grass, or sandy surfaces cannot retain water for long and quickly release the water to groundwater aquifers. Plants and plant litter reduce the rate of evaporation of soil water. Deforestation, or land-use which leads to degradation of the land, can thus alter the amount of water the soil can hold. Less moisture in the soil can limit plant growth and therefore carbon uptake.

Moisture feedback from the land and water bodies back to the atmosphere is an important part of climate regulation. A decline in moisture feedback (evaporation and evapotranspiration) can lead to changes in local and regional rainfall patterns.

> Box 13.1: Day Zero
>
> Cape Town is predicting that the municipal water supply will shut down and taps will run dry in 2019. The day this happens has been called "Day Zero".
>
> There have been predictions that Cape Town could run out of water since 1990. The cause of the water shortage is thought to be a combination of population growth (and therefore increased demand) and a drought in the Western Cape of South Africa which started in 2015 and is thought to be an impact of climate change.
>
> Current water consumption in Cape Town is approximately 200 billion litres per year (Pitt, 2018). Their goal is to reduce this to 165 billion – a ration of approximately 50 litres of water per person per day(Pitt, 2018). The World Health Organisation suggests that 50-100 litres are needed per person per day to ensure that most basic needs are met (UN, 2015a).
>
> Despite the water crisis, water is still being exported from the region as virtual water. In 2016, 428 billion litres were used in the production of wine for export and 112 billion litres were used for citrus exports. (Leahy, 2018)

13.3 A Global Problem

Water availability varies from region to region. In some areas, such as Southern Africa, water is scarce and droughts common. In other areas, local water availability is plentiful.

The regional availability of water has led to much controversy over the existence of a global limit for water. The main argument for those who do not believe in a global limit – is that it does not make sense for those with abundant water supplies to limit their showers and irrigation when the scale of their water consumption has negligible impact on the water bodies they are sourcing this from. They argue that there is no feasible way for water rich countries to transport their water to water scarce countries and as such, it does not make sense to consider this issue at a global scale. They reason that water saving measures should be prioritized in water stressed areas (Ridoutt and Huang, 2012).

Those who argue that a global limit does exist do not disagree that water savings should be prioritised in water stressed areas. However, they argue against the premise that water is not transportable. They contend that we transport virtual water, water used in goods and services, all over the world (see Figure 24). They reason that it is common of the use of products occurs in locations far removed from the point of virtual water consumption and that water is thus a global resource.

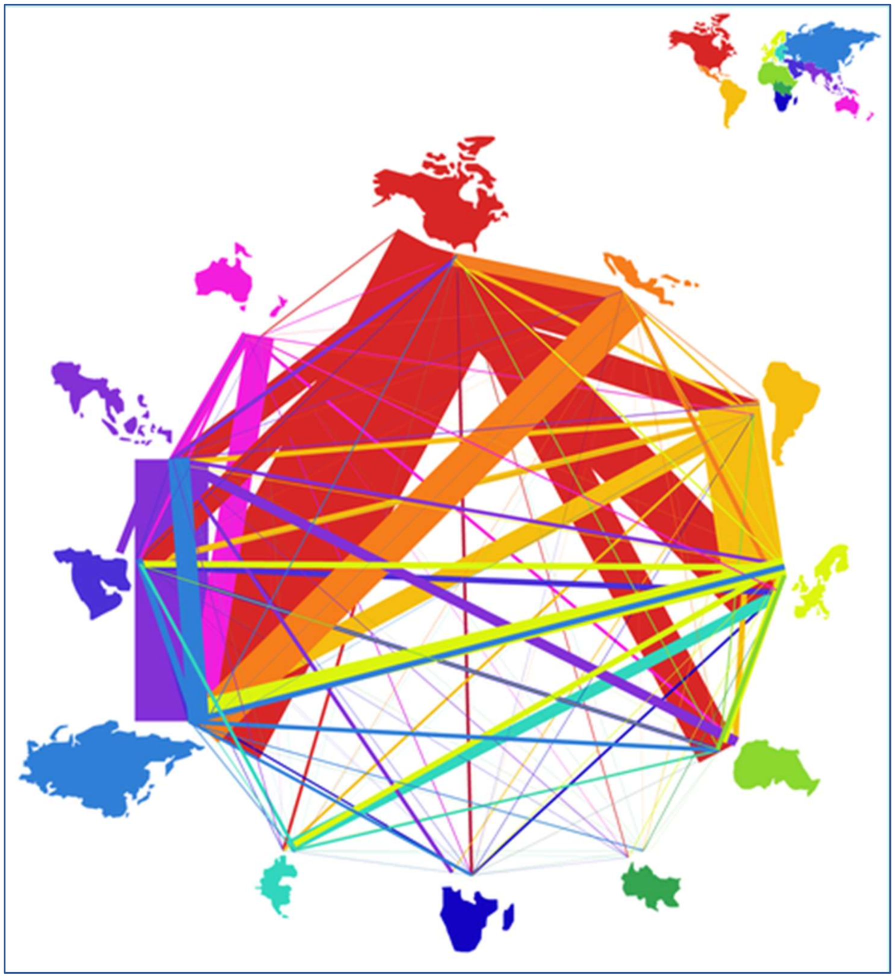

Figure 24: Virtual water imports and exports by region. Each band represents gross virtual water export from 1995-1999 (Porada, 2012)[25]

The Planetary Boundary (and the Planetary Quota) for water are based on the second point of view described above, i.e., that water is a global resource. The need for different responses in different situations (i.e., the need to urgently address water consumption in water scarce regions) is true for all of the PB to a varying extent. Countries with high reliance on fossil fuel energy will need to take greater and more urgent action towards reducing emissions than those in countries with mostly renewable energy for example. The argument of regional variability is present for any PB or PQ. The purpose of the PBs is to identify which

[25] With permission – see Appendix 4: Copyrights and Permissions

Earth System processes humans are altering that could put us at risk of changing the state of the Earth System. The water cycle is one of these processes.

Moreover, there are substantial efficiencies to be made by considering water as a global resource. This is likely to be one of the mechanisms which will help to resolve the over appropriation of water in water scarce regions. Governments typically look at water from a national perspective rather than considering impacts or opportunities from virtual water imports (Mekonnen and Hoekstra, 2011b). Yet, agricultural trade saved global water consumption of approximately 369 teralitres per year between 1996-2005.

Of the water saved through agricultural virtual water, approximately 59% was green water, 27% blue and 15% grey. The global blue water savings achieved account for 10% of the total global blue water footprint from agriculture. The implication of these figures is that those importing virtual water would have needed to use more blue water to produce the same quantity of products had they produced them locally (Mekonnen and Hoekstra, 2011a). International trade in industrial products is equivalent to 4% of the global water footprint related to industrial production (Mekonnen and Hoekstra, 2011b).

13.3.1 Weighting Water to Manage Regionality

There are two main schools of thought on environmental accounting for water. The first is that every litre of water should be counted equally, whether it is sourced from a water scarce location or not. This is the basis of the Water Footprint (Hoekstra and Wiedmann, 2014, Mekonnen and Hoekstra, 2016). The second is that water should be given a weighting factor to account for the source, i.e., one litre of water taken from a water scarce source might be environmentally equivalent to two or more litres of water taken from a water rich source. This is the basis of the Weighted Water Footprint (Pfister and Bayer, 2014, Ridoutt and Pfister, 2013, Ridoutt and Pfister, 2010).

There is no question that water bodies facing water scarcity need different management to those with an abundance of water. The idea of weighting water from different sources appeals to many.[26] However, it is an impractical solution to the problem if the goal is robust accounting of environmental currencies.

Consider Water Body A, an almost dry reservoir near Cape Town where there are severe water limitations, and Water Body B, a reservoir in Denmark with an abundance of water. It is clearly more sustainable to take a litre from Water Body B compare to Water Body A.

[26] During my extended peer community engagement, this topic was often the forefront of discussions and debate.

However, the suggestion to apply a weighting factor to represent this becomes very challenging. By how much, is it preferable to extract the litre from Water Body B? Is it 10 times better? 100 times?

Ridoutt and Pfister (2013) have proposed a mechanism for water accounting with which to account for water stress of water sources using a unit of *equivalent* water (H_2Oe) to determine the Weighted Water Footprint. Their proposal is based on a water stress index previously developed by the same authors (Pfister et al., 2009). The water stress index can range from 0.01 – 1 (it cannot be 0 in acknowledgement that every withdrawal has some impact) and is determined based on the availability of water and water withdrawals of a particular water body. One litre of H_2Oe is the burden on a water system of one litre of water at the global average WSI.

The solution is seemingly quite elegant, and appears similar to indicators such as *carbon dioxide equivalent (CO_2e)*, an indicator that allows the warming impacts of different greenhouse gasses to be expressed in terms of the amount of CO_2 that would produce the same amount of warming, *ozone depletion potential (ODP)* which indicates how much ozone will be depleted per kilogram of a substance compared to a kilogram of CFC-11, or *aerosol optical depth equivalent (AODe)* which is an estimation of the relative impacts of an activity on air quality. However, H_2Oe is fundamentally different. The calculation of H_2Oe is such that the weighted water footprint of an activity depends not only on the water consumed during an activity, but also by the amount of water others consume from the same water body.[27] This is inconsistent with any other environmental accounting practice. If someone releases 100kg of methane, this is worth 250kg of CO_2e, regardless of the activities of others. Likewise, 1kg of nitrous oxide always has an ozone depletion potential of 0.17 ODP kg.

The water scarcity index is very useful for local resource management as it gives a clear indication of the health of the water body. The problem with the weighted water footprint method is not that it is not accurate. If more users withdraw water from the same water source, the environmental impacts of each litre of water will be greater. The problem is that the method is not useful to understand and manage water impacts of consumers.

> For example, consider a CEO trying to reduce their weighted water footprint of her products. Her company is the only entity withdrawing water from a nearby lake, and

[27] The unit of H_2Oe depends on the water scarcity index which is a function of water availability and *water withdrawals.* So as total water withdrawals from a water body increase, so to does the water scarcity index and the H_2Oe of an activity.

> she is aware that her company is large fraction of the available water. She spends substantial time and effort reducing the water consumed by her company's processes and manages to reduce total water consumption by 50%. Over the same time period, a large company moves in nearby in the same period and this new company's withdrawals alter the water scarcity index of the water source by 50%. The CEO calculates the weighted water footprint of her products after the changes she has implemented and finds it has not changed.
>
> The new company has a very high weighted water footprint, and this CEO is getting a lot of pressure to reduce the impacts of his products. He doesn't see an easy way to improve water efficiency within his factory, so he sabotages the first company and puts them out of business. Now that the first company is no longer taking water from the lake, his weighted water footprint drops substantially, even though his net water consumption is unchanged.

The Water Footprint approach where every litre of water is counted equally provides a more robust metric for water management. A company's water footprint depends solely on the company's water consumption and not on the water consumption of others. In this way, the relative water efficiency of products is apparent regardless of the source of the water. The use of this method of water accounting does not preclude the consideration of the source of water being consumed. This information could be provided in addition to the total water consumption to give a holistic view of water impacts of a given activity. This is the approach proposed here.

<u>Box 13.2: Local vs Global Impacts</u>

The purpose of the Planetary Accounting Framework is to allow any scale of human activity to be compared to critical global limits. This does not preclude the need for local environmental management practices. This is not only true for water. There is high regional variation for many environmental impacts. Environmental flows which are not addressed by the Planetary Boundaries could be absolutely critical to some local ecosystems. The difference is that these are unlikely to push the balance of the Earth System function out of a Holocene-like state. The scarcity of water in a given water body might be of critical importance locally. However, it is scarcity of water at a global scale that risks altering the function of the Earth System

13.4 The Indicator

The Planetary Boundary control variable for global freshwater use is *gross consumptive blue water use* (Rockström et al., 2009a). The authors 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 green water, they set a consumptive blue water use limit as a preliminary measure (Rockström et al., 2009a, Steffen et al., 2015).

Gross consumptive blue water use is already a pressure indicator which can be scaled and applied directly to human activity. However, as shown in Table 26, not only water consumption but also water contamination must be considered in the Planetary Quota for water. Further, the exclusion of green water from the PQ is problematic when considering some of the potential applications of the PQs.

The Planetary Accounting Framework is not intended to be the solution for all environmental problems. It is designed to allow any scale of human activity to be compared to critical global limits. There are many local impacts that would not be considered by the Planetary Accounting Framework and thus would need to be dealt with at that scale. These impacts might be very critical to local ecosystems. The difference is that they are unlikely to push the balance of the Earth System function out of a Holocene-like state. The scarcity of water in a local water body is one such impact. Nonetheless, there are ways in which Planetary Accounting could be used to take into account some local impacts, including water scarcity of particular water bodies. These are discussed in Chapter 19.

13.4.1 Green vs Blue

The premise that blue water is a good indicator of total water consumption is arguable. Mekonnen and Hoekstra (2011) show that there is a close correlation between the green water footprint of a country and total water footprint, but little correlation between the total water footprint of a county and either the blue or grey water.

More importantly perhaps, when considering the exclusion of green water, is the consideration of the different purposes of the Planetary Boundaries compared to the Planetary Quotas. The Planetary Boundaries were developed to give a clear indication of overall Earth System health. The use of a proxy indicator for total water consumption in this instance still provides an indication of water consumption compared to availability.

In contrast, the purpose of the Planetary Quotas is to be able to assess the impacts of human activity against global limits. Some argue that the use of green water, for example to feed crops, is essentially "free" water on the basis that the water was going to fall in that area anyway. This is not an accurate account.

> Consider the example of a 1000-acre area in New Zealand. Originally, this area was native New Zealand forest – a very dense and damp ecosystem. The deep roots of New Zealand timbers – Kauri and Rimu and the deep leaf litter helped the soil to retain a high moisture content. Some of this water would slowly make its way to the ground water reserves below, – well filtered by the soil and free of contaminants. The rest of the moisture would be used by the plants, and other species in the forest, and returned to the atmosphere through evapotranspiration and transpiration, ready to fall as rain again.
>
> Today, the 1000 acres has been converted to pine forest. The rain falls, feeding the forest. Pines have higher water uptake than Rimu or Kauri so more water is removed from the soil, so that the soil becomes a little less moist over time. Nonetheless, the pines, like the Rimu and Kauri, transpire and release water back to the atmosphere. Then one day they reach maturity and are chopped down and removed from the site. All the rainwater that is currently held in the tree is removed from the cycle. Nutrients are applied to the soil and new trees are planted. The pines continue to dry out the soil as they absorb water more quickly than the natural level of rain fall. The degrading soil and shallower roots of the pine trees mean that water travels more quickly to the groundwater, with less filtration. Some of the natural and the added nutrients are carried away to aquifers. The soil degrades further. More pines are cut down, and more water is removed from the cycle. Over time, the soil degradation is too much, and the land becomes unsuited to forestry. The forest land is cut down and the land is converted to farmland or left as wasteland. Without trees, the water cycle changes. The rain falls, travels quickly through the soil, carrying nutrients away to local water bodies. The water bodies are starting to experience algal blooms because of all the additional nutrients carried from the soil. The soil degrades further. The grass or shrubs do not transpire as much as the trees, so less water is returned to the atmosphere. There is less moisture in the air, and therefore less rainfall.
>
> For comparison, consider a 1000-acre area in the United States. Originally this area was grassland. The rainfall was sporadic. It is now used to grow pine. When the rain falls, there is no need to irrigate the land. But for much of the year the land is irrigated

> from a water body not too far away that has a variable supply. The pine absorbs this blue water. It grows, it transpires, releasing water into the atmosphere. This falls back to the ground as rain. Some of this water makes its way back to the water body. However, over time, the water body is depleted. The pine is chopped down and taken away. All the blue water that is currently held in the tree is removed.

In planetary accounts, comparing the NZ and US timber described above, the inclusion or exclusion of green water is important. If only blue water was considered, the NZ pine trees would have a water impact of zero, whereas the US pine trees would have a water impact > 0. Yet, the amount of water used to grow these two pines is the same.

There are impacts from redirecting blue water or green water for human use. 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. Further, green water accounts for approximately 74% of the global average water footprint of production (Mekonnen and Hoekstra, 2011a). Excluding almost 3/4s of the global water footprint from the PQ for water would give an incomplete picture.

13.4.2 Gross water versus Net Water

The Planetary Boundary indicator is for *gross* water consumption. This means that all water extracted from water bodies is considered, regardless of what then happens to it. Water can be borrowed from the water cycle without substantial consequence, provided it is returned in an uncontaminated state and to the same general vicinity.

Given the purpose of the Planetary Quotas, it makes more sense to consider both the extraction and the disposal of water at the end of its use. Consider for example, two factories: Factory A and Factory B. They both produce baked beans, withdrawing the same amount of water per tin of beans from a local aquifer. Factory A dumps the waste water into the local river where it eventually makes its way, untreated, into the sea nearby. Factory B has onsite waste water treatment which treats the water to a very high standard. It is then returned to the local aquifer. The gross water consumption, the total water taken from the aquifer is the same. However, the impacts on water use by Factory A and Factory B are not equal. The net water consumption of Factory B is the water extracted from the aquifer minus the water returned to the aquifer.

Thus, the water consumption indicator for the PQ for water is for *net* water consumption.

13.4.3 Grey Water and Novel Entities

There are hundreds of thousands of man-made chemicals, materials, and substances which have the potential to cause harm to the Earth system. The potential effects of these substances are often poorly understood. CFCs are an example of man-made chemicals that were initially thought to be a breakthrough for many human needs – in particular refrigeration – as they were so much safer than previously used refrigerants. These substances that were touted for being harmless turned out to have serious, unexpected, global effects – thinning the ozone layer to the point that every spring there is a large area with almost no ozone at all (see Chapter 11).

The use and disposal of chemicals are the two critical pressures relating the Planetary Boundary for Novel Entities as shown in Table 26. However, although novel entities are included in the Planetary Boundaries framework, there is actually no limit or even a control variable proposed at this stage. The authors of the PB framework define Novel Entities as new substances, new forms of existing substances, and modified life-forms that have the potential of adverse effects to the geosphere or biosphere(Steffen et al., 2015). This definition includes chemical pollution which they define as radioactive compounds, heavy metals and organic compounds developed by humans, and materials or organisms engineered by humans such as nanomaterials and plastic which can degrade to microplastics.

Of the more than 100,000 chemicals on the market (Egeghy et al., 2012), only a few thousand have toxicity data (Rockström et al., 2009a). There is limited understanding of the combined effects of these chemicals. We are still learning about the impacts of other materials such as microplastics.

There is no single indicator that covers this array of environmental impacts at a pressure level. It is difficult to imagine an indicator that could assimilate these impacts. Yet the authors have included this unitless, limitless Planetary Boundary on the basis that a global boundary for novel entities does exist. They base this premise on two rationales:

1. The direct global impact on the physiological development of humans and other organisms which changes ecosystem function or structure
2. The indirect impacts on other Boundaries – for example, weakening species resilience to withstanding the impacts of climate change

In the absence of a suitable indicator with which to aggregate pollutants into a comprehensive single PB, the authors propose a twofold approach. Firstly, to focus on persistent pollutants that can travel long distances through the ocean or atmosphere such as mercury. The other is to identify unacceptable long-term and wide spread impacts.

The latter approach is most likely to lead to state or impact level[28] indicators. The authors deliberate over indicators such as reduced rates of or failed reproduction, neurobehavioral deficits, and compromised immune systems. The former lends itself to pressure level indicators. This approach is the basis of my approach here.

It is common practice to use water pollution as a proxy measure for chemical pollution (Bjørn et al., 2014). This is typically done by determining the dilution factor – the amount of water that would be needed to assimilate any pollution. This proxy indicator does not allow for all novel entities to be considered at this stage. Entities which do not make it to water bodies, and those which cannot be diluted (e.g., plastics), are not accounted for in a water pollution metric. However, using water pollution as a proxy indicator allows for chemical pollution to be included in the Planetary Quotas in some capacity. As such, the indicator for the PQ for water includes grey water to account for chemical pollution as an interim solution. More work will be required to develop a more robust way to measure and manage novel entities.

The indicator for the PQ for water is thus *net green, blue, and grey water consumption.*

13.5 The Limit

The Planetary Boundary for freshwater use is <4,000km^3/year of gross consumptive blue water use with an uncertainty zone of 4,000-6,000km$_3$/year (Rockström et al., 2009a). Consumptive use of blue water is about 2,600km^3/year (Steffen et al., 2015). It has been estimated that approximately 25-50% more blue water may be needed 2050 to ensure food security (Moden, 2007).

There is little agreement in the literature as to a global limit for net green, blue, and grey water consumption. It has been estimated that as much as 90% of green-water flows (Rockström et al., 1999) and 20-50% of blue-water flows (Smakhtin, 2008) are required to maintain ecosystems (including rainfed croplands). Global green-water availability is about 70,000 km^3/yr, and blue-water, about 12,500km^3/yr (Postel et al., 1996), so these limits would indicate that approximately 7,000km^3/yr of green water and a further 5,000km^3/yr of blue water could be consumed by humans – a total of 12,000 km^3/yr. Other authors suggest

[28] Indicators can be classified as *states, impacts, drivers, or pressures.* A state indicator is one that describes the state of the environment. An impact indicator is one that describes a change in the state of the environment. A pressure indicator is one that describes flows to the environment. Pressure indicators are the type of indicators used for the Planetary Quotas. See Chapter 6 for more details.

global blue water scarcity will be reached when withdrawals exceed 5000-6000 km^3/yr (Raskin et al., 1997, Vörösmarty et al., 2000, de Fraiture et al., 2001).

On the basis that more than 30% of major groundwater sources are currently being depleted, Hoekstra (2017) argues that we are already at the Boundary, if not beyond it, and that a precautionary approach would be to set the limit no higher than current net global water consumption ≈ 8500 km^3/yr (Hoekstra, 2017). Annual gross blue water consumption is approximately 2,600 km^3/yr. In contrast, annual net blue water consumption is approximately 1,000 km^3/yr (derived from (Mekonnen and Hoekstra, 2011b)). This would leave a quota of approximately 6,400 km^3/yr of green water, slightly below the maximum appropriation of green water proposed by (Rockström et al., 1999). The remaining 1,100 km^3/yr would be available as grey water to assimilate pollutants.

In the absence of an alternative basis for the limit for water consumption, the Planetary Quota for water is thus, net green, blue, and grey water consumption ≤8500km^3/yr.

This PQ can be compared to the water footprint as defined by Mekonnen and Hoekstra (2011b) for any scale of activity.

13.6 Discussion

The water footprint of the global average consumer between 1996-2005 was 1385m^3/yr. 92% of this was from agricultural products, 5% industrial goods, 4% for domestic water use. (Mekonnen and Hoekstra, 2011b). If everyone consumed the global average amount of water, the global water footprint at today's population would be over 10,000 km^3. Yet, approximately 780 million people do not have access to clean water and 2.5 million do not have access to sanitation (WWF, 2014b).

Falkenmark (1986) estimates that approximately 500m^3/p/year is needed to run a modern society. At the current population this would give a global water footprint of approximately 3800km^3/year. Even at a population of 9 billion this gives a total footprint of 4,500km^3/year. Both estimates are within the Planetary Quota for water.

> Box 3: Eating Water
>
> It is interesting to note that of the total global water footprint only 4% was for domestic water use. 92% was for agricultural products, nearly a third of this was related to the production of animal products. The consumption of meat accounts for 22% of the water footprint of the average consumer. The average WF per calorie of beef is 20 times larger than cereals and starchy roots (Mekonnen and Hoekstra, 2011a). Diet is thus one of the greatest contributors to the global water footprint.

Table 27 lists examples of activities at different scales to show how a poly-scalar approach to managing global water consumption might work at different scales of activity.

Table 27: Examples of different scales of activity which have or could contribute to achieving the PQ for water consumption

Achieving the Planetary Quota for Water Consumption			
Large	Develop global organisations dedicated to the management of global water resources *e.g. The Global Water Initiative*	Develop a global treaty for water management	Develop innovative low water technologies
Medium		Develop holistic national water strategies *e.g. Singapore is targeting the collection of every drop of water, the endless reuse of water, and desalination of sea water to meet national water demands*	Relocate water intensive activities to locations where water bodies are not suffering from water scarcity
Small	Install household or community grey-water recycling systems	Set local irrigation limit *e.g. Local councils in Perth, Western Australia, set irrigation rules such as the days that watering is allowed, and the number of minutes plants can be watered*	Choose water efficient raw materials for products
Individual	Eat a plant-based diet		Educate staff on water footprints
	Community	**Government**	**Business**

13.7 Conclusion

Water is a life essential and irreplaceable resource. Over 1/3rd of major groundwater aquifers are currently being depleted, suggesting that we are already consuming more than the planet's capacity.

The Planetary Boundary for water is in the unit gross, blue water consumption. The proposed PQ indicator is in net green, blue, and grey water consumption. The different indicator is to allow for more robust comparison of different human activities, to accommodate water management through water treatment strategies, and to incorporate the Planetary Boundary for novel entities.

The Planetary Quota for water is net blue, green, and grey water consumption ≤ 8,500 km^3/yr. This can be compared to the water footprint of any scale of activity. The limit is set on the basis of the current global water footprint.

CHAPTER 14

A Quota for Nitrogen

Abstract

Reactive nitrogen is necessary to grow food. It is often the limiting factor for plant growth and without it, farming yields would be substantially lower. However, the over use of nitrogen fertilisers has led to high levels of nutrient run off, causing algal blooms and therefore anaerobic dead zones in rivers, lakes, and oceans.

The Planetary Boundary for nitrogen is a maximum of 62 TgN/yr of intentionally fixated nitrogen. This indicator is scalable, but not easily comparable to human activity. Further, it does not consider downstream denitrification processes that can reduce the environmental impacts of nitrogen use.

The Planetary Quota indicator for nitrogen is *net nitrogen consumed* ≤ 62TgN*.* This includes virtual nitrogen that is lost to the environment during the production of food and accounts for the removal and recycling of nitrogen from the human nitrogen cycle. The limit is based on the premise that the Planetary Boundary value is based on the maximum flow of nitrogen to waterways. Net nitrogen consumed will eventually end in waterways. This limit can be compared to the nitrogen footprint of any scale of human activity. Current annual nitrogen consumption exceeds the PQ for nitrogen.

14.1 Introduction

Nitrogen is the most prevalent element in the Earth's atmosphere. Approximately 78% of the atmosphere (by volume) is nitrogen gas (N_2). Nitrogen is one of the fundamental building blocks of life. It is in chlorophyll – the green pigment in plants that is responsible for photosynthesis, it is a building block of protein, and is critical to other cellular elements that are essential to life (Wagner, 2011). However, in its most abundant form, a stable gas, it cannot be used by most living organisms. Reactive nitrogen (N_r) is the form of nitrogen that is needed for life. In contrast to nitrogen gas, reactive nitrogen is relatively scarce. A lack of available reactive nitrogen is often the limiting factor for natural ecosystems. This can also be the limiting factor for intentional human ecosystems (e.g. farms).

Excessive loss of reactive to the environment can have harmful impacts including eutrophication, smog, acid rain (which harms plant and aquatic life and infrastructure), and stratospheric ozone depletion (n-print, 2011). Nitrous dioxide (one form of reactive nitrogen) is also an important greenhouse gas (GHG) (see Chapter 9).

Table 28 shows the critical pressures pertaining to reactive nitrogen against the corresponding Planetary Quota (PQ) and Planetary Boundary (PB) indicators. Reactive nitrogen is considered within several PQs, not only the PQ for nitrogen. This is because of the different impacts of reactive nitrogen on the Earth System. The PQ for nitrogen is predominantly based around the impacts of nitrogen on water bodies i.e., eutrophication. The impacts of reactive nitrogen as a GHG or an aerosol precursor are considered in the PQs for methane and nitrous oxide, and aerosols respectively (see Chapters 9 and 10).

In the PB framework, the PB limits for nitrogen and phosphorous are both encompassed in the PB for biogeochemical flows. Phosphorous and nitrogen have many similar impacts on the environment. However, there is no pressure indicator which collectively measures the two substances. As such each has its own PQ.

Table 28: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicators, critical pressures, and corresponding PB indicators and limits pertaining to nitrogen

PQ Indicator	Critical Pressures	Corresponding PB indicator
Nitrogen released to the environment	Release of reactive nitrogen to the environment	Intentionally fixated nitrogen ≤ 62 TgN/yr
Methane and nitrous oxide (MeNO) emission (See Chapter 9)	Methane emissions	Radiative forcing ≤ 1 W/m^2 Extinction Rate ≤ 10 E/MSY[a] Aerosol optical depth 0.05 ≤ AODe[b] ≤ 0.1 Concentration of stratospheric ozone ≥ 290 (Dobson units)
	Nitrous oxide emissions	
Aerosol and precursor emissions (See Chapter 12)	Carbon monoxide emissions	Radiative forcing ≤ 1 W/m^2 Aerosol optical depth 0.05 ≤ AODe ≤ 0.1 Extinction rate ≤ 10 E/MSY[b]
	Non methane volatile organic compounds	
	Nitrate emissions	
	Sulphate emissions	
	Black carbon emissions	
	Organic carbon emissions	

Notes:

c. E/MSY – extinct species per million species per year
d. AODe – aerosol optical depth equivalent (see Chapter 12)

The inclusion of reactive nitrogen across several PQs does not constitute double counting for the purpose of planetary accounting. This is because each PQ must be respected. There is no mechanism with which to amalgamate the PQs into a single indicator or to offset one against another. However, if the PQs were going to be used as the basis for a tax scheme, it would be important to include a mechanism so that excess reactive nitrogen use was not charged more than once (see Chapter 17).

This chapter begins with an introduction to the nitrogen cycle, human use of nitrogen, and the critical environmental impacts from reactive nitrogen. The PQ indicator *net reactive nitrogen released to the environment* is presented and the case for the preliminary limit for nitrogen is made. The chapter concludes with a discussion of the PQ for nitrogen, and the types of actions that might be needed in order for humanity to live within this PQ.

14.2 Background

14.2.1 The Natural Nitrogen Cycle

As discussed in Chapter 8, the Earth System has natural biogeochemical cycles in which a chemical substance moves between the atmosphere, biosphere (life on Earth), lithosphere (Earth's crust), and hydrosphere (surface and atmospheric water). Nitrogen is one of the substances which moves through such a cycle.

There are five key processes in the nitrogen cycle: fixation, ammonification, nitrification, and denitrification.

Nitrogen Fixation

The most common form of nitrogen is N_2, two nitrogen atoms bonded together. This is very stable and unusable by plants. Nitrogen fixation is the process of converting nitrogen from this stable nitrogen gas form to useful forms ammonia (NH_3) and ammonium (NH_4). Natural nitrogen fixation is generally done by nitrogen-fixing bacteria through a metabolic process that is similar to the way humans and other animals convert oxygen (O_2) to carbon dioxide (CO_2) when we breath. The bacteria can be free-living in the soil or water, can be associated with plants (typically grasses – including rice, wheat, corn, oats, and barely), or can have a symbiotic relationship with plants (typically legumes such as alfalfa, beans, clover, peanuts, and soybeans). This biological fixation accounts for 90% of natural reactive nitrogen in terrestrial ecosystems.

The other natural form of nitrogen fixation occurs when high levels of energy are applied to nitrogen gas which breaks apart the nitrogen molecules, leaving them ready to make new bonds. The high energy can come from lightening, forest fires, and the heat from volcanic eruptions. Oxidised forms of nitrogen are produced in the atmosphere (NO_x) and then this settles to Earth's surface where it can be used assimilated by plants.

Together terrestrial ecosystems are estimated to release approximately 65 TgN/yr, and marine biological systems a further 140 TgN/yr,

Nitrification

Bacteria in the soil converts ammonium (NH_4) and ammonia (NH_3) to nitrite (NO_2) and then to nitrate (NO_3). This processes typically occurs aerobically. It is done exclusively by prokaryotes which are single-celled bacteria and cyanobacteria without a nucleus or membrane.

Assimilation

Assimilation is the absorption of ammonia or nitrate from soil by plants. Plants convert nitrate to nitrite ions and ammonium ions – the forms needed to become amino acids, nucleic acids, proteins, and chlorophyll. Animals (and humans) get their nitrogen from these plant tissues.

Ammonification

Ammonification is the reverse of assimilation. The organic nitrogen (proteins, acids) is converted back into ammonia. When plants and animals defecate, urinate, or die, the organic nitrogen is available to bacteria and fungi which can return it to ammonia. This ammonia is left in the environment ready for return through the cycle via nitrification or assimilation.

Denitrification

Nitrates and nitrites are converted back into nitrogen gas by bacteria in anaerobic conditions such as deep in the soil or near the water table. Wetlands are a very important part of the denitrification process. Denitrifying bacteria release nitrous oxide as well as nitrogen gas back into the atmosphere.

14.2.2 Human Use of Nitrogen

The management of nutrients in soil (including nitrogen) can be traced back in history to as early as 6000 BC – when Middle Eastern farmers practiced crop rotation. The Bible has reference to a "Sabbath of the Land" which meant that every seven years they would leave the land return to its natural state. Farming practices developed over the years from two-field rotation where only half of the land was farmed each year and the other half left to recover, to a three-field system, where two crops would be rotated both seasonally and annually and a third of the land would be rested every year. Four-field rotation began in the early 16th century – this included seasonal rotation, annual rotation, and importantly, rotated arable and livestock farming. The rotations all included leguminous and cereal crops which produced ammonia in the soil for the other crops. The addition of a livestock rotation increased the return of nitrogen to the soil through animal urine and faeces.

Biological N-fixation is slow and limited so in addition to crop rotations, the use of natural fertilisers was common. Manure, guano (bird droppings), and human waste, all of which are rich in nitrogen, were applied to fields to promote plant growth.

Throughout this time, farmers were reaping the benefits of well managed nutrients in the soil but without understanding the chemistry behind their actions. In 1840 Justus von Liebig discovered the important roles ammonia (one of the reactive forms of nitrogen, and later of phosphorous (discussed in Chapter 15) (Liebig, 1840). After his discovery, nitre mining for potassium nitrate for use as a fertiliser became common. However, at the beginning of the 20th century there were concerns that the demand for nitre would quickly outstrip the supply and research into sources of ammonia increased.

14.2.2.1 The Haber-Bosch Process and the Green Revolution

In 1909 Fritz Haber discovered a way to convert nitrogen gas into ammonia. He placed hydrogen and nitrogen gas under high pressure to force a chemical reaction that converted them to ammonia (NH3). The Baden Aniline and Soda Factory (BASF), a German chemical company, bought the process from Haber and assigned employee Carl Bosch to the job of scaling Haber's process up to an industrial scale. Bosch succeeded in 1910 and the procedure became known as the Haber-Bosch process.

The Haber-Bosch process occurred at a similar time to the start of phosphorous mining. This early 20th century period is thus known as the Green Revolution. Agricultural production grew exponentially, as did population growth. It is estimated that without the Haber-Bosch process only 3 billion people could be fed given current diets and agricultural practices (Erisman et al., 2008). Between 1900 – 2000 the population quadrupled, yet the agricultural area used to feed the global population only increased by 30% (de Vries et al., 2013b). Nitrogen and phosphorus fertiliser was not the only reason for the improvement in agricultural yield which allowed this to happen. Plant breeding, herbicides, and pesticides were also important factors. However, the newfound ability of humans to intentionally produce reactive nitrogen is one of the most important factors (De Vries et al., 2013a). In this period there was a 50-fold increase in nitrogen fertilisers. De Vries et al. (2013a) postulate that without fertiliser, a similar population growth would have required a proportional increase in agricultural area and thus other major environmental impacts such as high levels of biodiversity loss.

The Haber-Bosch process is still the primary method for developing nitrogen fertiliser used today. Ammonia is in fact one of the most highly produced inorganic chemicals. Projections are that more than 187 million tonnes of nitrogen fertiliser will be used in 2018 (FAO, 2017).

14.2.3 The Impacts of Nitrogen

Without human interference, approximately 0.5kg of N/ha/yr is deposited (Galloway et al., 2008). Now, for many places, average deposition is >10 kgN/ha/yr (Science Communication Unit, 2013a).

Approximately 75% of man-made reactive nitrogen is from N-fixation and the remaining 25% from fossil-fuel and biomass burning. All reactive nitrogen created through fossil-fuel combustion is lost to the environment (Leach et al., 2012). Most reactive nitrogen used in agriculture is lost to the air, soil, or water. Only a small proportion of nitrogen applied to agriculture is taken up by crops. Humans and other species do not absorb nitrogen, so all of the nitrogen taken up by crops and then consumed by livestock and people, is expelled in urine and faeces. In the case of livestock, some of this is returned to the natural nitrogen cycle. Before mono-cultural agriculture, this release of nutrients from livestock was how much of the land was fertilised. However, intensive mono-cultural grazing means that excessive levels of nitrogen are released to the environment – more than can be absorbed by the natural cycle.

Human waste used to be returned to land and the nutrients returned to their natural cycle. It is now released into water. It is possible to denitrify waste water – a process that removes approximately 90% of nitrogen from sewage. However, only a small proportion of global sewage is treated. Most of this nitrogen is released back into the environment.

Denitrifying bacteria not only produce nitrogen gas, they also produce nitrous oxide (N_2O), a dangerous greenhouse gas. The use of nitrogen fertiliser has led to large increases in the amount of N_2O released into the atmosphere from agriculture.

Total reactive nitrogen production in agriculture is more than double pre-industrial natural amount in terrestrial ecosystems (Science Communication Unit, 2013a). The nitrogen used in modern agriculture is leading to widespread environmental change (Rockström et al., 2009d). Human activity is altering the natural nitrogen cycle.

There are many local, but also global consequences from the use of human fixated nitrogen. Excessive use of nitrogen in agriculture leads to eutrophication of terrestrial ecosystems (De Vries et al., 2013a). Eutrophication is excessive nutrient richness which can cause high growth of plants such as algae – known as algal blooms – which in turn prevent oxygen and sunlight from reaching the water below. This can lead to hypoxic conditions, wiping out fish and other aquatic species. The die-off of algal blooms releases toxins into the water which can further reduce biodiversity in the area (de Vries et al., 2013b). This can change the function of the ecosystems and reduce biodiversity(De Vries et al., 2013a).

Nitrogen can cause acidification of soil and water. Airborne reactive nitrogen is one of the primary causes of acid rain. There are excessive nitrates in much of the world's drinking water which has negative health impacts (De Vries et al., 2013a). Airborne nitrogen particles are dangerous to human health and crop yields (de Vries et al., 2013b). Nitrogen dioxide (NO_2) is the dominant source of oxygen atoms for toxic, ground level ozone (O_3), while nitrous oxide leads to the depletion of the important layer of stratospheric ozone. Nitrous dioxide is one of the critical greenhouse gases that is causing climate change. Nitrogen leads to stratospheric ozone depletion. (Science Communication Unit, 2013a)

14.3 The Indicator

The existence of a global limit for nitrogen is debated in the literature on the basis that nitrogen impacts are location specific. In fact, some of the impacts are globally dispersed, for example the emissions of nitrous oxide from the use of nitrogen fertiliser. Moreover, the location of nitrogen use is often spatially distant to the location of the end use. The concept of virtual nitrogen, i.e., the nitrogen used in the production of products (similar to the concept virtual water (see Chapter 13)), allows us to better see the global distribution of a regional or local problem.

The Planetary Boundary indicator for nitrogen, the industrial and intentional biological fixation of nitrogen, is a pressure[29]. However, it is not a pressure that suits the requirements of the Planetary Quotas. It is very difficult to link the fixation of nitrogen to down-stream activities at different scales. A more scalable and applicable indicator would be the amount of fixated nitrogen used and lost to the environment.

A nitrogen footprint (NF) has been developed to measure reactive nitrogen used in human activities (Leach et al., 2012). This indicator assesses the net nitrogen released to the environment by human activity. The nitrogen considered is both direct nitrogen consumed, i.e. the nitrogen in the carrot, or steak that a person is eating and the virtual nitrogen. Virtual nitrogen is the nitrogen that has been lost to the environment down-stream. It includes the ammonia lost to the groundwater when growing the carrot, the nitrogen released in urine and manure before the cow was taken to the slaughter house, and the nitrous oxide

[29] Environmental indicators can be classed as States, Impacts, Drivers, or Pressures under the European Union DPSIR framework. Pressures describe flows to the environment and are the type of indicator used for the Planetary Quotas. See Chapter 5 for details.

emissions released from the burning of fossil fuels to transport the carrot and steak to the supermarket and then the person's house.

It is possible to remove nitrogen from waste water – industrial denitrification. As much as 90% of the nitrogen in sewage can be removed before the waste is released to the environment. The nitrogen footprint includes a mechanism to account for this positive behaviour by removing this amount from the footprint in the instance that wastewater will be treated.

The control variable used to assess nitrogen footprints is the *net reactive nitrogen released to the environment.* Unlike the Planetary-Boundary indicator, this Pressure indicator can be related directly to any human activity, as shown by its use in determining nitrogen footprints of people, products, and nations (Leach et al., 2012, Pierer et al., 2014).

14.4 The Limit

The PB limit for nitrogen is set at a point estimated to limit the impacts of agricultural nitrogen on the environment while still meeting the world's need for food (de Vries et al., 2013b). De Vries et al (de Vries et al., 2013b) assessed critical environmental limits for ammonia in the air, nitrous dioxide in the air, and nitrogen in surface runoff. They then estimated the minimum amount of nitrogen fertiliser needed to feed a future population of 9 billion people. They conclude from these assessments that an appropriate boundary would be a fixation rate of 62 – 100 TgN/yr. The authors of the Planetary Boundaries updated the limit to 62 TgN/yr, the most stringent end of the range.

This limit is lower than the estimated minimum nitrogen that would need to be fixated to feed the population at current average nitrogen use efficiency (the amount of nitrogen taken up by different plants) of 80 TgN/yr. However, the authors estimated that minimum N-fixation could drop to 50 TgN/yr with a nitrogen efficiency increase of 25%, an efficiency increased they deemed to be feasible (de Vries et al., 2013b).

The globally *intended nitrogen fixation* (the PB indicator) is not equivalent to the *net reactive nitrogen released to the environment* (the PQ indicator). However, the basis of the PB limit of 62 Tg/N (i.e., the maximum amount of N_r that can safely be released to the environment), is also an appropriate basis for the PQ indicator limit. As such, the PQ for nitrogen is net reactive nitrogen released to the environment ≤62 TgN/yr.

14.5 Discussion

There are currently approximately 112 TgN/yr released to the environment (derived from (Steffen et al., 2015, Keeler et al., 2016)), almost double the PQ for nitrogen. The authors of the PB framework suggest that the PB for nitrogen could be met with improved farming practices and innovations such as the use of human waste onto productive landscapes (Rockström et al., 2009a).

A study of potential reactive nitrogen reductions in the UK showed that reductions of up to 63% were possible leading to a per capita N-footprint of 10 kgN/person/yr (Stevens et al., 2014). Based on the current global population, and equal per-capita nitrogen Quota equates to approximately 8.3 tN/yr. At a future population of 9 billion, this would reduce to 6.9 tN/person/year.

Different foods have different nitrogen uptake efficiency (NUE). They higher the uptake, the less nitrogen lost before the food is consumed. The average NUE for animal proteins is very low – at about 8% (meaning that 92% of the nitrogen used to develop the food is lost to the environment before the food is consumed). Plant based food has an average NUE of 20%. The reason for the low efficiency in animal proteins is that nitrogen is lost both in the growing of the animal fodder, and in the animal waste (manure).

Table 29 shows examples of the sorts of activities that might be different across different scales and sectors in order to live within the PQ for nitrogen.

Table 29: Examples of different scales of activity which have or could contribute to achieving the PQ for nitrogen.

Achieving the Planetary Quota for Nitrogen			
Large	Develop a global organisation dedicated to the measurement of nitrogen use *e.g. n-print*	Develop a global agreement for nitrogen management	Develop innovative solutions to limit the release of nitrogen to the environment
Medium		Set maximum national nitrogen application rates	
Small	Community compost initiatives *e.g. Compost Revolution - Australia's largest community of composters and worm farmers comprising more than 30,000 households in Sydney*		Alter farming practices to include on-farm nitrogen cycling with manure from livestock to feed crops.
Individual	Eat an organic and plant based diet		Start a business to manage challenges of composting: *e.g. Steve Rickerby realised that office buildings were not composting due to lack of space to compost on site so started a business collecting compostable from offices, foodcourts, schools, universities, hotels, and cafes.*
	Community	**Government**	**Business**

14.6 Conclusions

Nitrogen is a critical element in food production. However, too much nitrogen can cause run-off of nitrogen into water ways. This can lead to algal blooms which can be very harmful to aquatic eco-systems.

The Planetary Quota for nitrogen is net nitrogen released to the environment through agriculture. This is to differentiate from nitrogen emissions through burning fossil fuels (for example) which are captured in the PQ for methane and nitrous oxide and the PQ for aerosols.

The limit for the PQ for nitrogen is the release of reactive nitrogen to the environment ≤ 62 TgN. This can be compared to the nitrogen footprint of any scale of human activity. The limit is based on the Planetary Boundary limit for maximum global nitrogen fixation.

CHAPTER 15

The Phosphorus Quota

"*Life can multiply until all the phosphorus has gone and then there is an inexorable halt which nothing can prevent*"

Isaac Asimov, 1974

Abstract

Phosphorus is a chemical element that is vital to all life on Earth. It is critical in the formation of genetic instructions, in the production of cells, in providing energy to live, and in the formation of seeds and fruit.

Before human interference, the phosphorous cycle was in balance. Phosphorus consumed by plants and animals was returned to the soil. Waterways transported phosphorous as needed for aquatic life. A slow weathering of phosphate rocks was matched by the slow formation of new rocks in phosphorus-rich ocean sediments.

Since the industrial revolution, humans have altered the phosphorus cycle. Humans are extracting millions of tonnes of mineral phosphate from rocks every year. This is applied to land as fertiliser to grow food, and then much of it is released as waste to waterways. There is some concern as to the level of remaining reserves of phosphate rock and whether we are likely to run out of this critical resource in the near-term. However, the reason for the inclusion of phosphorus in the Planetary Boundaries is not the potential supply shortfall but rather the potential environmental impacts. The excessive release of phosphorus to water can lead to algal blooms and thus anoxic events, wiping out entire ecosystems. This process is believed to have happened on a global scale in the past – creating anoxic oceans and driving a global mass extinction of marine life.

The Planetary Quota for phosphorus is 11 Gt/yr of phosphorus released to the environment. This is based on the Planetary Boundary for maximum flow of phosphorus to the sea. The limit can be compared to phosphorus released during any scale of human activity.

15.1 Introduction

The human-induced alterations of the phosphorus cycle are perhaps one of the least well known global environmental crises facing us today. Phosphorus is a chemical element that is essential to all life on Earth. It is the eleventh most abundant element in Earth's crust (Schröder et al., 2010). Phosphorus is an essential component of genetic material – DNA (deoxyribonucleic acid) and RNA (ribonucleic acid). It is necessary for the production of cell membranes, and for the creation of seeds and fruit which are fundamental to the life-cycle of fauna. All living organisms need phosphorus ever day to produce energy. Even bacteria need phosphorus to survive (Ashley et al., 2011). There is no alternative to phosphorus. There is no synthetic substitute. (Science Communication Unit, 2013b)

Phosphorus is very reactive so it is unusual to find it in it's pure form. The most common form is phosphate ($PO^{3-}{}_4$). Phosphates are the backbone of DNA. They are also a key component of Adenosine triphosphate (ATP), an important chemical which transfers energy (Ashley et al., 2011).

The name phosphorus comes from the Greek words *phôs* which means *light* and *phoros* which means *bearer*. Pure phosphorus glows in the dark (Ashley et al., 2011) and can sometimes be seen on the ocean surface at night. Humans mine phosphorus from phosphate rock for a variety of applications. The predominant use, which accounts for 90% of mined phosphorus, is for fertiliser and animal feed (Prud'homme, 2010). A further 7% is used in detergents, although this is declining as most high income countries do not allow its' use in detergents anymore (Liu et al., 2008). The small remaining amount of phosphorus is used as flame retardant, metal surface treatment, and in ceramic production (Liu et al., 2008).

Table 30 shows the Planetary Quota indicator against the corresponding critical pressure and Planetary Boundary.

Table 30: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicator, critical pressure, and corresponding PB indicators and limits

PQ Indicator	Critical Pressures	Corresponding PB
Phosphorous use	Phosphorous use	Phosphorous flow to the ocean ≤11 TgP/yr

This chapter begins with three sections that provide a background to phosphorus and its' use: an introduction to phosphorus and the phosphorus cycle; an overview of the history of human appropriation of phosphorus, and a discussion of phosphorus as a non-renewable resource. The second part of the chapter is about the Planetary Quota (PQ) for phosphorus. The chapter concludes with a discussion on how our current phosphorus use compares with the PQ for phosphorus, and what living within this PQ might mean practically.

15.2 The Phosphorous Cycle

Phosphorus is one of the chemical substances that moves between Earth's biosphere (life on Earth), lithosphere (Earth's crust), atmosphere (the layer of gases surrounding Earth), and the hydrosphere (surface and atmospheric water) naturally in one of Earth's biogeochemical cycles (see Chapter 8).

The phosphorus cycle can be broken down into three sub-cycles:

1. The inorganic phosphorus cycle: Phosphorus is accumulated as sediment on the sea floor. Over millions of years, the sediment is turned into rock through geological pressure. Tectonic shifts under Earth's crust expose phosphate rock. The exposed rocks are subject to weathering, releasing phosphorus back into the environment. (Föllmi, 1996, Schlesinger and Bernhardt, 2013)
2. The land-based organic phosphorus cycle: Plants take phosphorus from the soil. Plants are either eaten by animals, in which case the phosphorus is returned to the soil via urine and faeces, or when the plants die and decay, the phosphorus returns to the soil directly. It takes an average of one year for a molecule of phosphorus to complete this cycle. (Liu et al., 2008)
3. The water-based organic phosphorus cycle: Phosphorus is circulated between creatues in lakes, rivers and oceans. This is the most rapid cycle – it takes only weeks for a molecule to complete. (Liu et al., 2008)

Unlike the carbon, nitrogen, water, and oxygen cycles, the phosphorus cycle does not include a gaseous phase. As such, there is no atmospheric link between the land and the ocean other than the wind transport of phosphorus containing soil or water particles (Liu et al., 2008)

Before humans began mining phosphate rock, human use of phosphorus did not disturb the balance of the natural phosphorus cycle. However, over a relatively short period humans have extracted hundreds of millions of tonnes of mineral phosphorus from the inorganic phosphorus and released it into the organic phosphorus cycles with severe environmental consequences.

15.3 Human Use of Phosphorus – A Brief History

Phosphorus has a speckled history full of amazement and danger from the accidental discovery of phosphorus when burning urine to the use of phosphorus as a weapon. The use of phosphorus to improve crop yield has occurred unwittingly for over 40,000 years. The aboriginal “firestick” farming – burning of sections of forest to promote agricultural growth – was effective because the phosphorus in the ash was temporarily available for plants in otherwise very phosphorus poor soil (Cordell, 2001, Flannery, 1994) (see Figure 25).

Figure 25: Aboriginals making fire (Mützel, 1857)(PD[30]))

China used human waste (known as “night soil”) to fertilise land as early as 5,000 years ago (Ashley et al., 2011). Medieval English Lords let peasants graze their sheep on their land but punished them for removing any droppings (Driver et al., 1999).

German alchemist Hennig Brandt is earliest known to discover the pure form of phosphorus in 1669[31]. He did so somewhat accidentally, during his hunt for the philosopher’s stone – a stone that would turn base metals into gold. Brandt was distilling large quantities of urine, extracting phosphorus, and then cooling it to turn it into a solid (see Figure 26). Although the solid form did not achieve the goal of turning things to gold, it did glow in the dark. He did not reveal his discovery until 1675, when he and colleague Daniel Kraft became famous as they presented their new form of light. Phosphorus was not recognized as an element until a century later when Antoine Lavoisier, the founder of modern chemistry, finally recognized it as such. (Ashley et al., 2011)

[30] PD: This image has been released to the public domain

[31] There may have been earlier discoveries in ancient Rome however ASHLEY, K., CORDELL, D. & MAVINIC, D. 2011. A brief history of phosphorus: From the philosopher’s stone to nutrient recovery and reuse. *Chemosphere,* 84**,** 737-746.

Figure 26: The Alchemist in search of the philosophers stone ((Wright, 1771)(PD[32]))

From the 1700s to the early 1800s, phosphorus was used widely for medicinal phosphorus. Johann Linck was the first to sell phosphorus as a medicine in 1710. He suggested his pills could cure colic, asthmatic fevers, tetanus, apoplexy and gout. His pills allegedly contained 200mg of phosphorus. However, doses as low as 1mg/kg can be lethal so it seems his claims were somewhat exaggerated. In the mid-1700s, Dr Alphonse Leroy prescribed phosphorus as a sexual enhancement agent on the basis of self-experimentation. (Emsley, 2002)

The only medicinal purpose for which phosphorus was actually effective for was abortion, but at high risk to the mother. It is only a little more toxic to a foetus than the mother but in the late 19th century it was frequently used for this purpose. Women would scrape the heads off matches to access phosphorus. Over 1,400 events of poisoning were recorded in Sweden between 1851-1903. Only ten mothers survived (Shorter, 1991).

It was not until 1840 that people first understood the chemistry behind the phenoMe-NOn of dead and decaying matter created new life (Liebig, 1840, Ashley et al., 2011). Even once the chemistry was understood, human activity did not substantially alter the phosphorus cycle until much later. Famine and soil degradation led to the use of external sources of phosphorus. Phosphorus was removed from the soil with crops but it was replaced with organic phosphorus such as crushed or dissolved bones, guano(bird droppings), human waste, crop residue and manure (Emsley, 2002) (see Figure 27).

[32] PD: This image has been released to the public domain

Figure 27: Bison skulls were disolved for phosphorus ((Unkown, 1892) (CC PD 3.0[33]))

After World War II the use of mineral phosphorus from phosphate rocks grew exponentially (Science Communication Unit, 2013b). A combination of the sanitation revolution, which shifted the deposit of human excrement from land to water, and the green revolution – the discovery that phosphorus and nitrogen could improve crop yield, transformed agricultural practices.

As with many changes, the transition was not slow and linear, but abrupt and system changing. From 1950 – 2000 mineral-fertiliser use grew six fold (Science Communication Unit, 2013b). It became feasible to separate the production and consumption of crops over longer distances. Arable farming could now be separated from livestock farming. Manure went from being a valuable and important resource to a waste product. (Schröder et al., 2010)

15.3.1 The (Human) Phosphorus Cycle

The seeming efficiencies of phosphorus fertilizer came with many problems. Although crop yields increased, less care was taken with recycling waste products back into society. The

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previously circular, closed-loop system had become linear. Phosphorus was (and is still) extracted, used, and disposed of.

The life cycle of mined phosphorus is not only environmentally damaging but also hugely inefficient. Of the phosphorus mined for fertilizer, it is estimated that only one fifth is present by the time it is consumed (Cordell et al., 2009). The process, often termed "mine to fork", has losses and environmental impacts at every stage from the extraction and primary processing, to the processing, fertiliser application, to harvesting and post harvesting:

Extraction

Before phosphorus can be extracted, the mine site needs to be prepared. Impacts at this stage include the clearing of vegetation, topsoil removal, and the removal of overlying rock. These changes can lead to changes in surface and underground water flow patterns, topography, habitats, and biodiversity.

Both the mine preparation and the extraction of phosphorus are very energy-intensive processes and therefore incur high levels of associated CO_2 emissions. Other impacts include substantial water consumption and soil erosion. Approximately 18% of the phosphorous mined is lost through inefficiencies at this stage. (Prud'homme, 2010)

Primary Processing

Phosphate rock is often associated with contaminants such as cadmium which is toxic, and uranium which is radioactive. Not only phosphorus but also these contaminants can be lost to the environment during primary processing, i.e., beneficiation and cleaning. Average losses at this stage are 16%. (Schröder et al., 2010)

Processing

Approximately 14.9 MtP/yr is processed from phosphate rock into phosphate products. This can be done using acid (to develop fertiliser), or heat (to develop industrial phosphorus and feed phosphates). Phosphogypsum, a bi-product of processing phosphate into fertiliser using sulfuric acid, is one of the more harmful waste products in the human-phosphorus cycle. It is usually mixed with water to make a slurry and then deposited on land to allow the solids to settle out – a process known as wet stacking. The concern is that radioactive material in the slurry could leach into groundwater. Some phosphoic acid plants do not even take these precautions with wet stacking and simply release the slurry into freshwater bodies and even into the oceans (Wissa, 2003). Approximately four to five tonnes of phosphygypsum are generated per tonne of phosphoric acid. Phosphorus losses at the processing stage range from approximately 5% for acid processing to 10% for heat processing. (Prud'homme, 2010)

Fertiliser Application

Only a third of the phosphorus in fertilizers is absorbed by plants. The rest accumulates in soil (in which case it is not really lost as it is still available to future plants), is washed away by rainwater or is blown by the wind in soil or water particles. (Science Communication Unit, 2013b). There are other minor losses at this stage from pests and diseases, but this phosphorus is usually redeposited and available for plant use. The impacts of phosphorus lost to water bodies are the basis for the inclusion of phosphorus in the Planetary Boundaries framework (Rockström et al., 2009d). Phosphorus promotes algal growth which can lead to anoxic events that can wipe out entire ecosystems.

Harvest and Post-Harvest

During harvesting, crop residues such as husks account for further phosphorus losses. Some crop residues are left on site where they are generally returned to the soil. In this case the phosphorus is not lost as it can be reused in the next crop rotation.

Food waste, excreta, and animal-feed losses may account for as much as 30% additional losses during the post-harvest stage (Kantor et al., 1997).

At each stage there are also minor losses such as spillages, spoilage, theft, storage, transport (Isherwood, 2000).

As discussed above, some of the apparent losses are actually an accumulation in the soil. Little was known or considered about the different phosphorus needs of different soil types until recently and so in some cases, far more phosphorus has been applied than needed. In the Netherlands there is enough phosphorous in the soil to supply the country with phosphorous for the next 40 years (Wilt and Schuiling, n.d.).

Almost 100% of phosphorus consumed as food is excreted in urine and faeces. Approximately 70% is in urine, and the remaining 30% in faeces to a total of 3Mt/year. Less than 10% of this phosphorous is reused. Of this, most of this is used indirectly as untreated or treated wastewater, some as sludge, and some from ash (from incinerated sludge). A small amount is also used directly via composting toilets and direct defecation. The remaining 90% is discharged to water or land. (Cordell et al., 2009)

Past practices of phosphorus use, and management were sustainable as humans tapped into and expanded the natural phosphorus cycle without fundamentally altering it. In contrast, current use is unsustainable. We now take substantial amounts of phosphorus from the inorganic cycle, use it once, and release it into the organic cycle at rates that the organic cycle cannot process.

15.3.2 Phosphorus – a Non-Renewable Resource

Mineral phosphorous found in phosphate rock is a non-renewable resource as the rate of replenishment of phosphate in rock, which occurs over millions of years, is of a different order of magnitude than human activity. There are 4 $x10^{15}$ tonnes of phosphorous in the Earth's crust. Humans currently consume approximately $3x10^{6}$ tonnes of phosphorus per year (Schröder et al., 2010). The problem is that very little of the phosphorus in the crust is accessible. Much of the phosphorus that is accessible is either in such low concentrations that extraction is not economically viable, or there is too much contamination by other substances (MEA, 2005).

The exact amount of phosphate rock reserves are difficult to determine. Reserves are defined as phosphate rock that is accessible using existing technology and is economically viable. The most recent estimates by the International Fertiliser Development Centre IFDC (2010) are that 60,000 billion tonnes of phosphate rock reserves remain. This is substantially higher than the previous US Geological Survey estimate of 16,000 (Science Communication Unit, 2013b). As technology improves or as demand for phosphorus increases, the amount of phosphate rock that is deemed accessible or economically viable is likely to increase.

The question of whether we are facing an imminent supply shortage of phosphorus is debated in the literature. Estimates of the amount of the amount of high quality phosphate rock remaining range from only a few decades worth to a few hundred years (Schröder et al., 2010). Van Vuuren et al 2010 in (Science Communication Unit, 2013b) assessed phosphorous levels under different scenarios around agriculture, household and sewage systems and found that there were no signs of near term depletion. However, they did find that longer-term, low-cost, high-grade resources would be in short supply. This is consistent with other studies e.g. (Schröder et al., 2010, Science Communication Unit, 2013b).

Not only is phosphate rock non-renewable, it is also very unevenly distributed across the globe. Almost 75% of the known reserves are located in Morocco and Western Sahara. A further 20% is located in China, Algeria, Syria, Jordan, South Africa, the US, Russia, Peru, and Saudi Arabia. 95% of the reserves are controlled by only 10 countries. Of these countries, most of the exports are from Morocco and Jordan. China, the US and South Africa use their reserves inhouse. (Science Communication Unit, 2013b)

Moreover, the ownership structures of the mines and supply chains suggests market volatility is likely (Elser and Bennett, 2011). The mines in Morocco are state owned. Given the large proportion of global phosphorus that is located in Morocco, this puts the Moroccan government in a position of power to control the market price. Additionally, large parts of the supply chains globally (i.e. the mining, processing and fertiliser production) are operated by a single firm. This sort of vertical integration has been shown to increase the likelihood of monopolisation (De Ridder et al., 2012).

Most countries are heavily reliant on imports of phosphorous and there has already been evidence of market volatility. In 2008 there was an 800% price spike for phosphorous. After this spike, China imposed a 135% export tariff on phosphates (Fertiliser Week, 2008). The Arab Spring in Tunisia led to a 40% drop in exports of phosphorous (De Ridder et al., 2012).

15.4 An Indicator for Phosphorous

It is not the potential scarcity of phosphorus, but the environmental impacts of its' use that have led it to be included as a Planetary Boundary limit. When excessive levels of phosphorus make their way into water bodies, this can lead to algal blooms or eutrophication (Schröder et al., 2010). The intense blooms block sunlight from entering the water below which reduces the amount of oxygen dissolved in that water and creating anoxic conditions or "dead zones". Originally the sea had very little oxygen and only single-celled organisms with low oxygen needs were able to survive. As oxygen levels increased, so did aquatic life. However, there is evidence that there were at least partial returns to oxygen-free oceans in our history. Indeed, it is thought that past phosphorous inflow into the oceans may have been the primary cause of global scale ocean anoxic events which lead to mass extinctions of marine life (Handoh and Lenton, 2003). There are currently more than 400 costal dead zones in the oceans from phosphorous with large dead zones in the Gulf of Mexico, the Baltic sea, and the Atlantic off west Africa. The environmental impacts of algal blooms continue after the death of the algae as this releases toxic compounds which can also kill fish in surrounding waters (Correll, 1998).

There are requirements to treat wastewater to prevent this from occurring in many developed countries with regulations such as the Urban Wastewater Treatment Directive (EEC, 1991). However, the success of these regulations varies. In Europe the amount of water treated ranges from 4% to more than 97% (OECD, 2004).

The primary Planetary Boundary limit for phosphorous is a flow of no more than 11 TgP/yr from freshwater systems to the ocean. This limit is set at a point where the risk of a global anoxic ocean event is considered low. There is also a secondary limit of a flow of no more than 6.2TgP/yr from fertilisers to erodible soils. (Rockström et al., 2009c)

The PB control variable is a pressure indicator[34]. However, in this instance, the flow is describing the movement of a substance between environments. It is not describing a flow from human activity. This means that it is difficult to compare this control variable directly to human activity, one of the criteria for selecting PQ indicators (see Chapter 7). However, the maximum flow of phosphorus from freshwater systems to the ocean is the amount of phosphorus released to the environment by human activity. This is also a pressure indicator, and one which can be easily related to any scale of human activity. As such, this is the indicator selected for the PQ for phosphorus.

15.5 The Limits

Over a long timeframe, it can be assumed that almost all phosphorus released to the environment by humans will end up in the oceans. As such, the PQ limit for phosphorus should be the same as the PB limit. This means that the PQ for phosphorus is *net phosphorous released to the environment* ≤ 11 Tg/yr.

15.6 Discussion

The current rate of phosphorus flowing from freshwater systems to the ocean is approximately 22Tg/year. This means that the PQ for phosphorus is currently being exceeded.

Table 31 lists examples of activities which could occur at different scales and across different areas of the community in order to manage human use of phosphorus.

[34] Environmental indicators can be classified as Drivers, Pressures, States and Impacts under the EU DPSIR framework. A Pressure is an indicator that describes an environmental flow, and is also the category of indicator used for the Planetary Quotas. See Chapter 5 for further details.

Table 31: Examples of different scales of activity which have or could contribute to achieving the PQ for phosphorus.

Achieving the Planetary Quota for Phosphorus			
Large	Develop a global organisation dedicated to the measurement and management of phosphorus use	Develop legislation around maximum phosphorus applications and phosphorus-management practices	Develop phosphorus recycling techniques to reduce demand on raw phosphorous supplies and supply of waste phosphorous to waterways
Medium	Campaign for greater awareness about the environmental impacts of phosphorus		Build a business around phosphorus recycling
Small	Community composting		
Individual	Eat an organic and plant-based diet		
	Community	**Government**	**Business**

15.7 Conclusions

Phosphorus is a non-renewable substance that is critical to life on Earth. However, human use of mined phosphorus as fertiliser is having severe downstream impacts. The nutrient can stimulant unnatural levels of algal growth that cause anoxic events that can wipe out entire ecosystems.

The Planetary Quota for phosphorous is net phosphorous released to the environment ≤ 11Tg/yr. This can be compared to the amount of phosphorous released during any scale of human activity. The limit is set on the basis of the Planetary Boundary for phosphorous flow to the oceans.

CHAPTER 16

The Biodiversity Quota

Abstract

Recent human activity has had more severe impacts on species loss than any other period in human history. Despite efforts to manage this, the impacts are continuing to increase. Biodiversity is very important to the Earth-system function and to humanity directly because of the ecosystem services it provides.

It is extremely difficult to link biosphere health to human activity as there are so many different ways that human activity can be damaging to the biosphere. A new proxy indicator has been developed by the UNEP to link land use to pressures on biosphere integrity – percentage disappearing species.

The Planetary Quota for biodiversity is percentage disappeared fraction of species ≤ $1x10^{-4}$/yr.

16.1 Introduction

The extinction of species is a natural process. Almost every species that has ever lived on Earth is already extinct. Species extinction will occur with or without human intervention. However, as a result of human activity, the current rate of biodiversity loss is 10-100 times greater than estimated natural rates. (Secretariat of the CBD, 2001)

Biodiversity can be defined as the extent of variability in plant and animal species. Biodiversity is critical to the functioning of the Earth System. Different species play different roles in an ecosystem, and the loss of one species can sometimes mean the collapse of an entire ecosystem. The bee for example is responsible for the pollination of many different plant species. Without the bee, many of these plants risk dying out. Species with particularly important roles within their ecosystems are referred to as keystone species.

Some believe that managing human impacts on biodiversity is a far more challenging task than reducing emissions as it is so difficult to attribute species threats to human activity (Moran et al., 2016, Vačkář, 2012). Consumers are often very disconnected from the impacts of their consumption on biodiversity health. In one study, as much as 44% of the threats to species from net exporting countries were found to occur outside the national boundaries (Lenzen et al., 2012a).

Of the nine Planetary Boundaries, biosphere integrity is one of the limits we have transgressed the most. It is also the most interconnected PB. The PB indicator for biodiversity loss, extinction rate, corresponds to every Planetary Quota (PQ) (see Chapter 7, Table 10). This high level of interconnectivity has led the PB for biosphere integrity to be considered as one of two core PBs (climate change being the other). Both are intrinsically connected with almost every other PB.

While every PQ Indicator corresponds to extinction rate, it is not the case that every critical pressure relating to extinction rate can be addressed by other PQs. Table 32 is a modified excerpt from Table 10 in Chapter 7. It shows the critical pressures that remain to be addressed by the PQ for biodiversity, and the corresponding PB indicators and limits.

Table 32: Modified excerpt from Chapter 7, Table 10 showing the PQ Indicator, critical pressures, and corresponding PB indicators and limits

PQ Indicator	Critical Pressures	Corresponding PB
Percentage Disappearing Fraction (PDF) (of species)	Land conversion	Radiative forcing ≤ ±1 W/m^2
	Land segregation	Aerosol optical depth ≤ 0.1 (AOD)[a]
	Land degradation	Extinction rate ≤ 10E/MSY[b] Remaining forest ≥ 75% original
	Introduction of species	Extinction rate ≤ 10E/MSY
	Overexploitation of species	

Notes:

a. AOD – aerosol optical depth, a unitless dimension indicating the amount of aerosols in the atmosphere
b. E/MSY – extinct species per million species per year

This table shows two critical pressures separately to the others – the introduction and overexploitation of species. It is very difficult to assign a suitable indicator or limit for these variables. As such, they are included under the proxy indicator percentage disappearing species.

This chapter shows how the PQs can be used to connecting human activity to unwanted biodiversity-loss outcomes. It begins with some background about species extinctions – the main drivers, and the past mass-extinction events. This is followed by an overview of how biodiversity health and in particular how the relationship between this and human activity has been measured. The case is then made for the proxy indicator and proposed PQ limit. The chapter concludes by putting this limit into context and providing examples of the sorts of activity that might be needed to address this PQ.

16.2 Background

The biosphere is the part of Earth where there is life – a thin envelope around Earth's surface. Most organisms depend directly or indirectly on sunlight, so life is predominantly located where sunlight has access – i.e., the surface, the atmosphere, the upper layers of the oceans and lakes, and the top layer of soil. There is life deeper in the oceans and in Earth's crust – bacteria live almost everywhere. A new project is underway to drill into Earth's mantle to determine, among other things, whether there are bacteria or any forms of life in Earth's mantle. Biodiversity is highest at the equator and reduces towards the poles, with moist forests in the tropics providing the greatest species-richness (Secretariat of the CBD, 2001).

Humans rely on biodiversity to fill many functions, often referred to as ecosystem services. The second report by the Convention on Biological Diversity listed twenty-four ecosystem services performed by species in the biosphere (Secretariat of the CBD, 2006). Ecosystem services include:

- ecosystem services such as the provision of food from plants and animals;
- the provision of resources such as timber and bioenergy, biotechnology (the use of living organisms such as yeast for bread and beer);
- regulating services including as water filtration, decomposition of organic waste, and climate regulation; and
- supporting services such as nutrient cycling (e.g. the nitrogen and phosphorous cycles) and photosynthesis.

Genetic diversity is the diversity of the genetic makeup of a single species. Genetic diversity is important. It helps species to be flexible in harsh conditions such as climate change, storms, or widespread outbreaks of pests (Secretariat of the CBD, 2001). Genetic material taken from wild species is used to improve crops, develop drugs, and as raw materials for use in products and services.

Diversity of species and within species is necessary for resilient ecosystems and for a resilient biosphere. There are also moral, ethical, cultural, aesthetic, and scientific reasons to conserve biodiversity. However, it is biodiversity's role in the regulation of the Earth System that is the basis for the Planetary Boundary for biosphere integrity.

Fossil records lead us to expect approximately one species to become extinct every 400 years (birds) and 800 years (mammals). Over the last 400 years it is estimated that we have been losing twenty to twenty-five species every 100 years. This is 100 to 200 times the base level. Species extinction can only be measured through negative evidence i.e., a lack of species. This means that monitoring of extinction rates is very limited, and it is hard to say how many species have gone extinct over a period or to predict likely future extinctions. It is possible that the extinction rates are substantially higher than those estimated. To accumulate negative evidence there is substantial lag as until sufficient time has passed, it is hard to say whether there are few or none of a particular species (Mace et al., 2014b).

Most known plant and animal extinctions have been on islands and most continental extinctions have been freshwater organisms. There are few extinctions recorded in continental rainforests. However, the monitoring of this is extremely difficult. The rate of *known* biodiversity loss in the oceans is much less than in any other type of ecosystem. This may be due to a lack of knowledge of the extinctions but is also likely to be related to the size of the oceans and the fact that people don't live in them permanently.

Human activity is generally thought to negatively impact biodiversity. In the case of genetic biodiversity however, human activity can and has both reduced and increased diversity (Secretariat of the CBD, 2001). Humans have been indirectly but purposefully manipulating biodiversity for more than 10,000 years. This has led to the current high diversity of domesticated crops and livestock. The manipulation has been indirect because the focus was on preserving or developing features rather than genes themselves, for example, efforts to increase pest resistance or milk yield. Humans also alter genetic diversity intentionally through genetic engineering. This is the introduction of a section of DNA from one organism into another, where it wouldn't naturally occur, to produce a genetically modified organism (GMO) with favourable properties.

Although human activity does influence biodiversity in both directions, it is overwhelmingly harmful. In the last 50 years, human activity has had more impacts on biodiversity than in any other period in human history (MEA, 2005). Despite increased efforts to reduce impacts, it has been estimated that the impacts would continue to worsen until at least 2020 (Secretariat of the CBD, 2014, Tittensor et al., 2014).

Between 2000 and 2012, 0.5 Mkm^3 of tropical rainforests – the most biodiversity rich habitats - were destroyed (Hansen et al., 2013b). Human activity has led to increases in global average temperatures that have shifted and eliminated habitats. In the late 1990s marine capture fisheries was almost 90million tonnes. FAO say that almost all marine stocks are widely over exploited. Other impacts on marine ecosystems include waste disposal, recreation, costal stabilisation and transportation. Chemical pollution and eutrophication is widespread. Fishery operation can also destroy the seabed and effect population levels of non-target species. Commercial bottom fishing disturbs sea-floor organisms and the seabed impacting both habitats and species.

Biodiversity loss can cause permanent changes to the planet (Rockström et al., 2009a). Changes to the planet can also cause permanent and extensive biodiversity loss. A global mass extinction is defined as a period where more than 75% of species become extinct. This has happened five times in known history.

<u>Ordovician-Silurian Extinction</u>

The first known global mass extinction occurred approximately 444 million years ago, at the end of the Ordovician period. Approximately 85% of species were lost. There are thought to have been two drivers for the extinctions - a brief but severe ice age and falling sea levels. Both drivers may have been the result of the uplifting of the Appalachians – a mountain range. The mountains were previously unexposed silicate rock. Once exposed, the silicate rapidly absorbed CO_2 out of the atmosphere leading to rapid global cooling. The changing land mass and glaciation could have driven the sea-level fall. (Harper et al., 2014)

Late Devonian Extinction

The second mass extinction is thought to have occurred approximately 375 million years ago during the Devonian period. 75% of species were lost. It is thought that new land plants with deep roots may have caused the extinctions. The roots stirred up the earth, releasing nutrients into the ocean. This may have triggered algal blooms that sucked the oxygen out of the water, suffocating marine species.

Permian-Triassic Extinction

The third mass extinction event occurred at the end of the Permian period – approximately 251 million years ago. This was the worst extinction event, known as "the great dying", with a species toll of 96%. Scientists suggest that this event set life back by 300 million years. The event is believed to have been set in motion by a volcanic eruption near Siberia. Huge amounts of CO_2 were released into the atmosphere. In response, bacteria released vast quantities of methane. The greenhouse gases warmed the atmosphere while the high levels of CO_2 in the atmosphere caused the oceans to become acidic and stagnated.

Triassic-Jurassic Extinction

200 years ago, at the end of the Triassic period saw a loss of 80% of species. There is no clear cause for this mass extinction.

Cretaceous-Paleogene Extinction

66 million years ago, was the most recent, and best known of the mass extinction – the demise of the dinosaurs. This was caused by an asteroid hitting Earth.

The current rate of known species loss is of an order of magnitude that is approaching that of these global major extinction events (Chapin et al., 2000).

16.2.1 Biodiversity Management

There have been efforts to preserve biodiversity on a global scale since the 1980s. In 1988 the United Nations Environment Programme (UNEP) convened the Ad Hoc Working Group of Experts on Biological Diversity. The following year UNEP started the Ad Hoc Working Group of Technical and Legal Experts later known as the Intergovernmental Negotiating Committee, who were tasked with the development of a legal framework for conserving biodiversity.

Their work became the Convention on Biological Diversity (CBD) which was adopted in Nairobi in 1992. It entered into force in December 1993. (CBD, 2018)

The CBD is a legally-binding global treaty. It covers:

- conservation of biodiversity;
- sustainable use of its components; and
- fair and equitable sharing of benefits rising from the use of genetic resources.

Participation in the convention is nearly universal. In 2001 the CBD produced its first periodical report on the state of global biodiversity – Global Biodiversity Outlook 1. There have been four such reports, the most recent released in 2014.

In 2002 the conference of the parties adopted a Strategic Plan with the mission "to achieve, by 2010, a significant reduction of the current rate of biodiversity loss at the global, regional and national level, as a contribution to poverty alleviation and to benefit all life on Earth". It was endorsed by the Heads of State and Government at the World Summit on Sustainable Development in Johannesburg. At the 2005 World Summit of the United Nations (UN), world leaders reiterated their commitment to the 2010 targets. (Secretariat of the CBD, 2006)

The COP established supporting goals and targets and identified indicators for evaluating biodiversity status and trends (Secretariat of the CBD, 2006). The targets were not met (Butchart et al., 2010). It is thought that the failure to meet the targets is because efforts were not aimed at the underlying causes of biodiversity loss (Secretariat of the CBD, 2010). The responses were predominantly focussed on the direct pressures and on the state of biodiversity. (Secretariat of the CBD, 2010).

The UN General Assembly designated the period 2011 – 2020 as the UN Decade on Biodiversity. The CBD developed a Strategic Plan for Biodiversity from 2011 – 2020 with a 2050 vision of the end to biodiversity loss and move to sustainable use of ecosystems. This included five strategic goals and 20 Aichi Targets. (Secretariat of the CBD, 2014).

Box 16.1. Poly-scalar management and biodiversity

There is a lot of reference to poly-scalar management approaches within the CBD reports:

- In the second report from the CBD (2006) the authors highlighted the need for action at all levels, i.e., a polyscalar approach (see Chapter 3).
- In the third report the idea was repeated. The report suggests: *"biodiversity loss could be slowed and even stopped if Governments and society took coordinated action at a number of levels"*.
- In the 2011-2020 strategic plan the point was made again, this time with more strength: "*the basis of the Stategic Plan is that biodiversity loss can only be effectively addressed with simultaneous and coordinated action at a number of levels, each of which is essential to achieve a lasting impact and to set us on a sustainable path to keep human societies within the limits of the planet's biological resources".*
- In the fourth report, the CBD repeated the need to address underlying drivers through change at all levels (Secretariat of the CBD, 2014). However, within the same report is the statement "*It is therefore an appropriate opportunity to review progress towards the goals of the Strategic Plan, and to assess what further action governments may need to take to achieve the targets they collectively committed to in 2010*".

It is promising to see that the science of governance and change is becoming integrated with efforts to manage the environment.

16.2.2 Measuring Biodiversity Health

There is currently no consensus on best ways to measure biodiversity health (Moran et al., 2016). It is difficult to accurately assess the health of biodiversity in a given ecosystem. It is even harder to relate threats to biodiversity to human activity.

A biodiversity footprint has been proposed – as the number of species threatened due to land conversion, land-use changes, unsustainable use of natural resources, over-exploitation of marine ecosystems, and invasive alien species (Lenzen et al., 2012a, Cucek et al., 2012).

However, this indicator is still an Impact indicator. The measure does not relate to the drivers, but to the outcome – the “number of species threatened”.

Some authors have attempted to connect biodiversity health to human activity. Asafu-Adjaye (2003) found that, while economic growth has an adverse effect on biodiversity, the composition of the economic output is important. There is a theory called the Kuznets hypothesis, which is that environmental impacts will increase with higher affluence to a certain point but then reduce as affluence grows beyond this point. Dietz and Adger (2003) tested this hypothesis for biodiversity loss but found that the curve did not exist. Another study concurred that the curve wasn’t present for most taxonomic groups (Naidoo and Adamowicz, 2001). However, these authors found that the number of threatened birds did drop as gross national product increased. As a general rule, the number of threatened species increases with population and with gross national product.

A new, binary certification has recently been developed to account for whether or not a product or sector exerts pressure on endangered species (Moran et al., 2016). This is a tidy parallel to the PB indicator – extinction rate. Such a system could potentially be used to certify products as Biodiversity (BD) Certified to account for the biodiversity pressures not included through the PQs. Moran et al. use a 1 or 0 for each sector – either they do exert pressure or they don’t. They do not attempt to measure the amount of pressure. They use four case studies to identify that environmental impacts can be traced to products through supply chain via input-output analysis. This information could also be included in a “planetary facts” product labelling system (see Chapter 16). Environmental labelling has been widely used to indicate impacts to consumers (Moran et al., 2016). This binary certification system would address the difficulty of communicating whether or not a product or service was impacting species extinctions. However, this indicator cannot be scaled, allocated, or easily connected to any scale of activity. It is thus not suitable as the PQ indicator.

The Leontief Calculus (1986), a model for the economics of a country or region, has also been used to connect final consumers with upstream biodiversity impacts. The basis of the model is to determine the quantity of a primary resource, for example coal, that would be needed to supply $1 of demand for every consumer in the country or region. Lenzen et al. (2012b) have used this concept to determine the number of species endangered by the development of a product by determining the impacts per dollar of product for a given year. The problem with this method is that it relies on input-output calculations which are typically based on national level imports and exports. Very few countries have input-output tables at a sub-national level.

16.3 The Indicator

There is both a global, and a regional Planetary Boundary for biosphere integrity (Steffen et al., 2015):

- Global: ≤ 10 extinction per million species per year (E/MSY) (with an aspirational goal of ≤ 1 E/MSY)
- Regional: Biodiversity Intactness Index of ≥ 90% (with uncertainty range 90%-30%)

The global PB is based on the extinction rate over the past several million years (Steffen et al., 2015). In both the first and second PB articles, the authors expressed a high level of uncertainty around both the control variable and the threshold for this PB. The proposed control variable has been criticised for being difficult to assess accurately or in a timely manner, and importantly, for being an unsuitable metric to apply to different scales (Mace et al., 2014b).

The drivers of species extinctions, or biodiversity loss, are complex and not completely understood (Secretariat of the CBD, 2014, Vačkář, 2012). However, most of the literature agrees that the five primary anthropogenic threats contributing biodiversity loss are:

a) climate change – shifting habitat to an extent that it is no longer suitable for the threatened species;
b) pollution that affects the health of species;
c) overexploitation of species, especially due to fishing and hunting but also overuse of ecosystem services leading to aforementioned habitat loss;
d) spread of invasive species or genes outcompeting endogenous species; and
e) habitat loss, fragmentation or change, especially due to agriculture, large-scale forestry, and human infrastructure.

(Galli et al., 2014, Rockström et al., 2009a, Cucek et al., 2012, Secretariat of the CBD, 2014, MEA, 2005)

There is some debate as to the relative impacts of these threats with respect to one another. In one study comparing threats to species in the united states, land-use was found to be the greatest threat, effecting 85% of species. Invasive alien species was found to be the second highest threat for most species, affecting 49%. However, pollution was the second highest threat for aquatic species. (Wilcove et al., 1998).

Lenzen et al. (2012a) have estimated that 30% of global species threats, excluding threats from invasive alien species, can be attributed to international trade. The same study showed that for the net importing countries studied, as much as 44% of their biodiversity footprint occurred outside of their national boundaries. This means that net exporting countries have very high biodiversity tolls. Approximately 35% of the threats to biodiversity in net exporting countries were related to production for export.

Others believe the most significant impact is change in land use such as conversion of ecosystems into agricultural and urban areas, changes to frequency, duration or magnitude of wildfires, and introduction of new species (Secretariat of the CBD, 2010, MEA, 2005, Fahrig, 2001, Groombridge, 1992, Bibby, 1994, Ehrlich, 1994, Thomas et al., 1994, Wilcove et al., 1998)

The first global report on biodiversity (Secretariat of the CBD, 2001) differentiates specific threats to species based on ecosystem type. The threats listed in this report can each be classified under one of the five key threats identified above. Table 33 shows that most of the key threats are applicable to most types of ecosystem.

The second global report on biodiversity (Secretariat of the CBD, 2006) shows the extent and trend of impacts from the five key anthropogenic threats on different ecosystems. Almost all the threats are shown to be either continuing in magnitude or increasing for almost all ecosystems. Of the five threats, all except climate change, already show high to very high impacts on biodiversity in at least some ecosystems. Climate change has had relatively low impact so far but is anticipated to have "very rapidly increasing impacts". Each of the five threats is discussed in more detail below.

Table 33: Shows key threats to biodiversity identified for different ecosystems in GBO1 under the five threat categories identified in the literature

Ecosystem	Habitat loss/change	Pollution	Climate change	Overexploitation	Introduced Species
inland water ecosystems	• Alteration and destruction of habitat through water drainage, canalisation and flood-control • Construction of dams and reservoirs • Sedimentation	• Sedimentation • Pollution: ○ eutrophication; ○ acid deposition; salinization; ○ heavy metals.			• Introduced species;
Forests	• Conversion, to cropland and plantations • Conversion to urban or industrial land • Fragmentation • Changing fire regimes	• Pollutants, including acid rain	• Changing fire regimes • Climate change,	• Logging • Extraction of non-timber forest products • Fuelwood extraction • Hunting • Unsustainable shifting cultivation	• Invasive alien species
Drylands	• Conversion, to cropland	• Chemical inputs - artificial enrichment	• Changing fire regimes. • Climate change	• Water use • Depletion of groundwater resources • Harvest of wood for fuel • Overharvest of wild species	• Introduced herbivores, particularly livestock, • Introduction of pathogens • Introduction of non-native plants.

Climate change

Climate change effects biodiversity in several different ways. Changes in season temperatures or durations can lead to early flowering or egg laying, and longer or shorter growing seasons (Secretariat of the CBD, 2014).

As global average temperatures increase, climate zones move. This is a gradual process, and in general, species will move with the shifting climate zones. The problem arises when the species cannot relocate. This is particularly problematic for island and mountain creatures. On islands, species movement is limited by island boundaries. On mountains, the extent of warmer zones from the mountain base tends to move higher and higher, reducing the habitable zone for some creatures until the point that there is no habitat left. In other instance, it can be human infrastructure that prevents species from relocating to more suitable climate zones.

When species do manage to relocate, this can be problematic in itself. Ecosystems operate in a natural balance that can be disturbed by the introduction of new species – sometimes to a point of destruction of the ecosystem functioning, or the extinction of one or more species. In this way, climate change can be a vector for the introduction of invasive alien species. Changing climates can also provide more favourable conditions for invasive or weedy species. The International Panel for Climate Change predicts that global warming will lead to increased species extinctions, although there is low agreement as to the extent of this (IPCC, 2014a).

There are two Planetary Boundaries for climate change – one for maximum levels of carbon dioxide in the atmosphere, and one maximum change to radiative forcing (the energy balance at Earth's surface). The PB for carbon dioxide is addressed through the PQ for carbon dioxide (see Chapter 7). The PB for radiative forcing is addressed through the PQs for carbon dioxide, methane and nitrous oxide (see Chapter 8), forest land (see Chapter 9), ozone (see Chapter 10) and aerosols (see Chapter 11). As such, the PQ for biodiversity loss does not need to further address this threat to biodiversity.

Pollution

Pollution is a very broad term that can be simplified by categorising this as water, land, and air pollution. Water impacts can be further divided into eutrophication (from the release of phosphorous and nitrogen into waterways) and chemical pollution.

The release of nutrients such as nitrogen and phosphorous into the environment poses a very significant threat to biodiversity and ecosystem services globally. Nitrogen and phosphorous fertilisers lower plant diversity and can lead to excessive levels of nutrients in water bodies. The nutrients can lead to dense plant and algal growth (algal blooms). This is known as eutrophication. Eutrophication can deplete oxygen and solar access to water bodies, wiping out entire ecosystems. (Secretariat of the CBD, 2014, MEA, 2005)

Other pollutants of continuing or growing concern can be generally categorised using the same terminology used in the Planetary Boundaries framework – as the release of novel entities into the environment. This includes plastics, in particular their impacts on marine ecosystems, heavy metals, and manmade chemicals which includes endocrine disrupters and pesticides, which have been implicated by some studies in damage to pollinating insect and bird populations. Overall, damage from marine oil spills has declined, due to better tanker design and improved navigation, but pollution from pipelines, mainly land-based, has increased due to ageing infrastructure. (Secretariat of the CBD, 2014).

Air pollution is caused by the release of chemicals, aerosols, and precursor gases into the environment. Particulate matter in the atmosphere with particle sizes less than 2.5 micrometres ($PM_{2.5}$) is considered the most harmful to human health. It is assumed that this can be taken as a proxy measure for human and biodiversity health.

Air pollution is addressed through the PQ for aerosols (see Chapter 11). Water pollution is addressed through PQs for water (see Chapter 12), nitrogen (see Chapter 13), phosphorous (see Chapter 14). As such, pollution does not need to be further addressed in the PQ for biodiversity. As discussed in Chapter 12, it is very difficult to address all novel entities through a quota approach, and thus, grey water contamination is used as a proxy for novel entities. Further work is needed to consider ways to address novel entities such as plastic more robustly.

The overexploitation of species

The overexploitation of species refers to the harvesting of species at rates higher than population recovery rates of that species. Hunting, and especially fishing are considered the two primary drivers. (Secretariat of the CBD, 2001). Bushmeat hunting can result in empty forest syndrome which is serious for the forest – 75% of tropical trees depend on animals to disperse their seeds. (Secretariat of the CBD, 2010)

Overfishing and destructive fishing methods have affected approximately 55% of reefs (Secretariat of the CBD, 2014). According to a UN report (2010), more than 80% of global fish stocks are fully exploited or overexploited. The Food and Agriculture Organisation (FAO) estimates that we have already reached the maximum wild capture potential for fisheries globally (FAO, 2010).

Worm et al. (2009) showed that 63% of 166 assessed fish stocks (the majority of which were well managed, developed country fisheries) have lower biomass levels than required to obtain maximum sustainable yield (MSY). Costello et al. (2012) found that 64% of fisheries had lower stock biomass than required to support MSY, including 18% that were collapsed.

Large marine protected areas (MPAs) already in place or pending establishment offer opportunities for better protection of coral reefs. Where there are well enforced MPAs that are coupled with land-based protection, there has been some success in reinstating fish stocks and coral recovery. However only 15% of MPAs have successfully reduced threats from fishing. (Secretariat of the CBD, 2014)

Birds are often hunted for sport with millions of birds traded internationally each year. Mammals have been hunted for a long time however today it is predominantly illegal hunting that threatens mammals – particularly large species.

There are no pressure indicators which encompass the overexploitation of species. There are various indicators around the appropriation of specific groups of species, in particular fish. For example, the “maximum sustainable yield” for fisheries is aimed at preventing the over harvesting of fisheries. There are no indicators which encompass overexploitation over the broad scale of human impacts.

Introduction of species

Species introduced into new environments, whether deliberately or accidentally, have contributed to more than half of the animal extinctions for which the cause is known (Secretariat of the CBD, 2014). Globalisation has led to a substantial increase in invasive alien species (including disease organisms)(MEA, 2005) Species invasions also carry enormous economic costs (Secretariat of the CBD, 2014).

The introduction of invasive species has many different pathways. A study by the Convention on Biodiversity CBD (2014) 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 6 major groups – release, escape, transport-contamination, transport-stowaway, corridor, and unaided.

Target 9 of the Aichi targets is that by 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment. Eradication programs on islands have been extremely successful but mainland eradication mostly unsuccessful (Secretariat of the CBD, 2014).

Although 55% of countries party to the CBD have policies regarding invasive species most of these are regarding boarder control and eradication with very few looking at identifying, prioritising and managing pathways of introduction (Secretariat of the CBD, 2014). The relationship between trade and biodiversity loss is not simple. More trade leads to increased pressures (through many things but particularly alien species) but also might allow for more efficient things therefore reducing net impacts per unit of product. (Secretariat of the CBD, 2006).

There are no pressure indicators which encompass the diverse pathways of invasive species introductions.

Land-use change

Land-use change is considered by many to be the greatest threat to biodiversity (Secretariat of the CBD, 2010, MEA, 2005, Fahrig, 2001, Groombridge, 1992, Bibby, 1994, Ehrlich, 1994, Thomas et al., 1994). Kerr and Currie (1995) did a study that looked at different measures of anthropogenic influence on biodiversity loss. Unlike other studies, they did not find that habitat loss was a prime contributor. However, in a study of threats to imperilled species in the United States found that habitat destruction and degradation was the greatest threat for 85% of the species analysed.

The biggest driver of land-use change is agriculture (MEA, 2005). Population growth is also leading to expansion into formerly natural areas (Fahrig, 2001). Hydro-electric power stations are considered to be a sustainable alternative to fossil fuel energy. They are also a major contributor to habitat loss as hydroelectric dam floods habitats (Secretariat of the CBD, 2014). More than one quarter of Earth's terrestrial surface area is already cultivated. A further 10-20% of grassland and forestland is expected to be converted to cultivated land before 2050 (MEA, 2005) .

The impacts of land-use change are both direct and indirect. Direct impacts include the destruction, alteration, and fragmentation of habitats. Felling of forests can eliminate habitats for some species. Trawling of sea beds can damage important marine habitats. Indirect impacts include the release of nutrients into waterways and withdrawals of water for irrigation and the segregation of habitats. (MEA, 2005)

There has been substantial growth in protected areas and many believe such areas are important (Lovejoy, 2006). The fact remains that biodiversity is declining even in the face of increasing protected areas (Butchart et al., 2010).

As shown in Section 16.2.2 there are a wide range of human driven factors that influence biodiversity loss that would be very difficult to combine into a single pressure indicator[35]. However, the high level of interconnectivity between biodiversity loss and other Planetary Boundaries is such that many of the threats are already considered under other Planetary Quotas.

Habitat loss and destruction is considered to some extent through the Planetary Quota for forest land. However, forest is not the only land type that is important. Further, the impacts on biodiversity change with different land types. The threat of habitat loss and destruction requires further consideration through a PQ for biodiversity.

16.3.1 A land-based proxy indicator

The magnitude and diversity of human drivers and pressures with respect to biodiversity loss makes it very difficult to determine one or even 2-3 indicators which can address the drivers and pressures holistically. Land use or ecological footprint, water, nitrogen, phosphorus and carbon impacts have all been used as proxy indicators for biodiversity loss. There have been a few attempts at developing a “biodiversity footprint”, however these are typically given in State based indicators and are therefore unsuitable for the Biodiversity Quota e.g. (Hanafiah et al., 2012, Houdet and Germaneau, 2014, Moran et al., 2016). There have been some attempts at defining consumption-based biodiversity metrics e.g., (Kitzes et al., 2017). However, these have not yet been developed to point that they could be used for the Biodiversity Quota.

[35] Environmental indicators can be classified as Drivers, Pressures, States, and Impacts using the EU DPSIR framework. Pressure indicators are the type of indicators used for the Planetary Quotas as they can be easily related to human activity and applied at different scales. See Chapter 6 for more detail.

As previously stated, land use is considered by many to be the greatest threat to biodiversity. It is also an accessible metric. For this reason, the use of land-based indicators as a proxy for biodiversity is common practice. Sustainable Development Goal (SDG) 15 is to “sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss” It is the most explicit SDG with respect to biodiversity loss, and includes several land based indicators in their proposal of suitable indicators to measure this goal including (UN, 2015b):

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

The Ecological Footprint is often used as a proxy indicator for biodiversity health on the basis that it is a measure of how much biologically productive land is used by humans. Some level of overexploitation of marine and terrestrial species is taken into account in this metric (Galli et al., 2014). The problem with using this indicator is that there is little consensus as to an appropriate limit. As discussed in Chapter 4, the term “biodiversity buffer” refers to the amount of global biological capacity that should be left aside for the maintenance of biosphere integrity. The suggested biodiversity buffer ranges greatly.

The Ecological Footprint authors proposed a minimum buffer of 12%, a level that was seconded in the Brundtland Report (Wackernagel et al., 2002, The Brundtland Commission, 1987). Soulé and Sanjayan (1998) interviewed 25 conservation leaders, biologists and agency personal about what levels would be sufficient. Biologists interviewed suggested that safeguarding 10% could make at least 50% of terrestrial species at risk of anthropogenic extinction (Soulé and Sanjayan, 1998). The authors who completed these interviews suggest that 50% is consistent with ecosystem surveys. However, their conclusion is based on very limited studies and low minimum thresholds. In order to estimate the minimum threshold, several studies have been undertaken to estimate how much of existing ecosystems would need to be maintained (by area) in order to maintain all existing species. For example, a study of Australian river valleys showed that 44.9% of wetland areas were required to represent each species once. However to have each species at least once AND represent all wetland types required 75% of wetland areas (Margules et al., 1988). In the Oregon coast range the authors found that 49% of the ecosystems were required to capture regions of high biodiversity, represent all ecosystems, maintain target species and provide for connectivity. In Norway 75% of habitat was found to be necessary to protect all plant species in deciduous forests and Florida, and 33.3% to preserve habitats essential for rare and declining species. Fahrig's study "how much habitat is enough" (Fahrig, 2001) found that extinction thresholds ranged from less than 1% habitat to over 99% habitat, demonstrating that a single figure for habitat protection is unrealistic.

Galli et al (2014) have written a paper *Ecological Footprint: Implications for Biodiversity* which is intended to demonstrate how ecological footprint could be used as an indicator in reducing biodiversity loss; they do not propose a minimum biodiversity buffer. Recommendations for a suitable buffer range widely.

There is no robust way to draw a parallel from the Planetary Boundary limit for extinction rate and a biodiversity buffer using the Ecological Footprint.

In a UNEP report on life cycle indicators, the need for a scalable indicator to assess the land use related impacts on biodiversity was identified and a new indicator proposed(UNEP, 2016). 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.

This sort of indicator does not address overexploitation or alien invasive species. As discussed previously, it is very hard to assess either of these threats using pressure indicators. As such, the *percentage disappeared fraction (of species)* is proposed as a proxy 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 Framework 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.

16.4 The Limit

The indicator *percentage disappeared fraction* differs from the Planetary Boundary indicator *extinction rate* only in the measurement/calculation method. The unit of measure is fundamentally the same. As such the Planetary Quota for biodiversity is ≤ $1x10^{-4}$/yr (PDF).

16.5 Discussion

The current PDF can be estimated to be of an order of magnitude between $1x10^{-3}$/yr and $1x10^{-2}$/yr, i.e., 10-100 times greater than the PQ[36]. This indicates that current land-use is not amenable to biosphere health. Table 34 shows examples of different activities that occur or could occur at different scales and across different sectors to reduce the PDF.

Table 34: Examples of different scales of activity which have or could contribute to achieving the PQ for biosphere integrity

Achieving the Planetary Quota for Biosphere Integrity			
Large	Set up a global organisation dedicated to the protection of biodiversity *e.g., the Global Biodiversity Outlook*	Develop an international treaty for biodiversity management *e.g. the Convention on Biological Diversity*	Set a precedent by ensuring no business operations have an impact on biodiversity health
Medium	Lobby to prevent land changes with high impacts on biodiversity *e.g. lobbyists were instrumental in stopping a controversial highway development in Western Australia, Roe 8, which would have led to the destruction of critical local habitats including the Beeliar wetlands*	Design national strategies for habitat zones and biodiversity corridors to connect different habitat zones through urban areas	Review biodiversity practices up and down supply chains
Small	Plant native species	Protect areas of biological importance	
Individual	Plant native species		

[36] These figures are based on global extinction rates as no global PDF has yet been determined

	Community	Government	Business

It should be noted that the proposed indicator, percentage disappearing fraction, is a relatively new indicator. It has been developed by a reputable source, i.e., the UNEP. However, work will be needed to assess the reliability of this.

Conclusion

The Planetary Boundary for biosphere integrity has been exceeded by between 10 and 100 times. Biosphere integrity is the most highly-connected Planetary Boundary, almost every Boundary has an impact on biosphere health. The drivers of biodiversity loss are complex and there is yet to be a metric proposed that deals with these holistically. However, there is a new proxy indicator based on land use that has been developed specifically to estimate human impacts on biodiversity. This is the basis of the Planetary Quota for biosphere integrity which is no more than $1x10^{-4}$/yr percentage disappearing fraction (of species).

CHAPTER 17

The Planetary Quotas and the Planetary Accounting Framework

Abstract

There is a need for a poly-scalar approach to Earth System management. Such an approach should be one which is integrative across different scales, sectors, and timeframes, that is not controlled by a single body, but which could be implemented through governance, privatisation, or self-organised management, that is coordinated by a general system of rules which have different mechanisms at different centres of activity.

Planetary Accounting is the act of comparing the impacts of human activity to scientific global limits. For example, carbon accounting against a global carbon budget is one stream of planetary accounting. The high-level Planetary Accounting Framework developed through this research project is a formal method of planetary accounting using nine global limits– the Planetary Quotas.

The Planetary Quotas are limits for human impacts on the environment. Each is a global limit given in environmental currencies such as carbon emissions, water use, and deforestation rate. The Planetary Quotas are derived from the Planetary Boundaries, global limits for Earth

System processes which define a safe operating space for humanity. Where the Planetary Boundaries are the health check for the Earth System, the Planetary Quotas are the prescription for a healthy planet. They show what is needed to return to and maintain planetary health

The Planetary Accounting Framework outlines how the Planetary Quotas can be applied to different scales of activity and for different purposes. The Framework sets out the important steps for applying the Planetary Quots: determining the parameters of an environmental impact assessment for different planetary accounts; selecting an appropriate way to scale the global Quotas to the scale of the assessment; and undertaking an environmental impact accessment. The output of planetary accounting is an *impact balance statement* which shows the credits or deficits in each environmental currency.

The Planetary Accounting Framework shows how the Planetary Quotas can be used to inform policy and governance, business operations, legislation, design and technology, and behaviour change programs. The high-level Planetary Accounting Framework and Planetary Quotas have the flexibility and high resolution needed to form the general system of rules for a poly-scalar approach to Earth System management.

17.1 Introduction

In the first section of this thesis, a gap in the literature was identified – the need for a new set of global limits that are communicated in terms of pressure indicators[37] that can be directly compared to any scale or type of human activity, Planetary Quotas (PQs).

In Section 2, the methodology and methods used to develop the Planetary Quotas and a framework outlining how to apply these, the Planetary Accounting Framework (PAF), was described.

Chapters 8 to 16 of Section 3 describe the results – giving details of each of the nine PQs.

The PQs form the foundations of the PAF. The PAF is a high-level framework that sets out the process of comparing different scales of human activity to global limits. As shown in Figure 28, this framework provides the platform (or bridge) for behavioural, policy, technological, and organisational change.

This chapter concludes Section 3 by detailing the PQs as a full set of global limits and describing how the PAF can be used to apply these. It includes a discussion of allocation methodologies and shows how the PAF has the flexibility to be applied across different methodologies rather than necessitating the selection of one over another. This chapter also includes a discussion about some of the specifics of this research as well as some of the strengths and weaknesses.

[37] Environmental indicators can be classified as Drivers, Pressures, States, or Impacts. The Planetary Quotas are in Pressure indicators which describe flows to the environment. This is because this sort of indicator is the most straightforward to apply to human activity at different scales. See Chapter 6 for more detail.

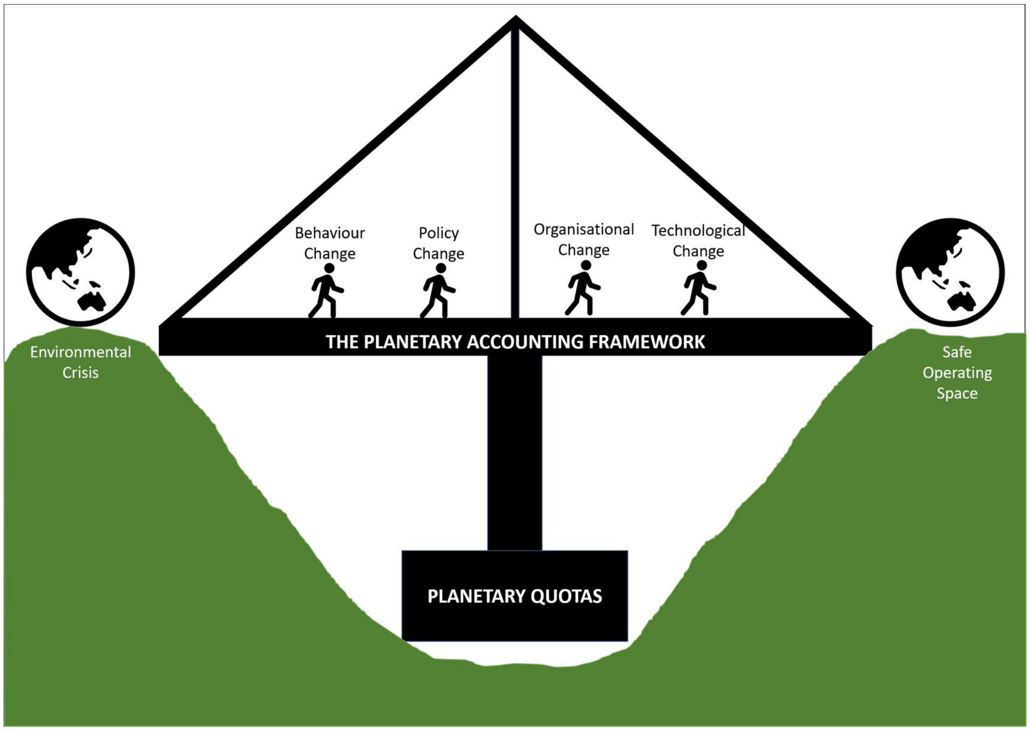

Figure 28: The Planetary Quotas provide the foundation for the Planetary Accounting Framework. The framework is the bridge that will enable change at all levels of human activity

17.2 The Planetary Quotas

Figure 29 shows the Planetary Quotas – nine environmental currencies with global limits. Each PQ can be allocated to different scales of activity including individual, city, business, sector, and national scales.

Table 35 summarises the nine Planetary Quotas, showing the indicators and preliminary limits for each. Table 36 shows the global status against each of the PQs. Seven of the nine PQs are currently being exceed, the PQs for carbon, methane and nitrous oxide (MeNO), forestland, biodiversity, nitrogen, and phosphorus, and Montreal gas emissions. Current water consumption is at the PQ limit for water. Current impacts have not yet been assessed for the aerosol emissions.

Table 35: The Planetary Quotas

Environmental Currency	Planetary Quota (control variable and limit)	Description of Control Variable
Carbon	Net carbon emissions ≤ -2.6 $GtCO_2/yr$	Net CO_2 emissions (including land use and land-use change emissions)
Methane and nitrous oxide (MeNO)	MeNO emissions ≤ 5.4 $GtCO_2e/yr$	Net warming potential of methane and nitrous oxide emissions to the atmosphere (in CO_2e)
Forestland	Deforestation rate ≤ -11Mha/yr	Net deforestation rate
Aerosols	0.04 ≤ AODe ≤ 0.1	Air quality impacts of emissions of aerosols and precursor gases expressed in *equivalent aerosol optical depth*
Ozone	Montreal gas emissions ≈0 ODP Kg/yr	Emission of gases controlled or due to be controlled under the Montreal Protocol in terms ozone depleting equivalence.
Nitrogen	Net nitrogen release ≤62 TgN/yr	Net release of reactive nitrogen released to the environment
Phosphorous	Net phosphorous release ≤11 TgP/yr	Net release of phosphorus to the environment
Water	Net water consumption $\leq 8500 km^3/yr$	Net green, blue and grey water footprint[a]
Biodiversity	PDF $\leq 1x10^{-4}/yr$	Net percentage disappearing fraction of species due to land occupation and transformation

Notes:

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

Table 36: 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 Currency	Limit	Estimate of Current Global Status
Carbon emissions	≤ -7.3 $GtCO_2$/yr	36 $GtCO_2$/yr [a]
Me-NO emissions	≤ 5.4$GtCO_2$e/yr	11 $GtCO_2$e/yr [b]
Deforestation rate	≤ -11Mha/yr	6.5 Mha/yr [c]
Aerosol emissions	≥ 0.04, and ≤ 0.1	Data not available but likely exceeded [d]
Montreal gas emissions	≈0 ODP tonnes/yr	32,000 ODP t/yr [e]
Nitrogen release	≤62 TgN/yr	150 Tg/yr [f]
Phosphorous release	≤11 TgP/yr	22 Tg/yr (Steffen et al., 2015)
Water consumption	≤8500 km^3/yr	8500 km^3/yr[h]
Biodiversity	≤ 1E-4/yr	$1x10^{-2} – 1x10^{-3}$/yr[h]

Notes:

a. (World Bank, 2009)
b. Derived from (World Bank, 2009)
c. (FAO, 2016)
d. In 2016, 92% of the world’s population lived in areas that exceed the World Health Organisation ambient air quality guidelines(WHO, 2016). This suggests this Quota (which is based on these guidelines) has been exceeded.
e. (UN, 2016)
f. (Steffen et al., 2015)
g. (Hoekstra, 2017)
h. Based on background extinction rate of 100-1000 extinctions per million species per year (Steffen et al., 2015)

It is important to note that exceeding a Planetary Quota is not the same as exceeding a Planetary Boundary. The PQs do not relate to the state of the environment. Rather, they are about the annual impacts of human activity. As such, it is possible to be exceeding a PQ, whilst remaining within corresponding PBs, and vice versa. What we know from the PQs is the direction of change. If for example, we were able to operate within the PQs for carbon, we would be moving towards the PB for atmospheric carbon dioxide. However, it would take a long time to return to within this PB. Likewise, although we have not currently exceeded the PB for water, if we operate beyond the PQ for water it is likely that we will exceed the PB in time.

As described in Chapter 6, the difference between the Planetary Boundaries can be compared to the management of human health. When a person goes for a health check, he will be given information that describes the state of his health – his blood pressure, heart rate, weight, and white cell count are examples of bodily process checks that might be assessed. Based on this information, the person knows whether he is in good health or not, and, if he is not healthy, he also knows which areas require the most focus.

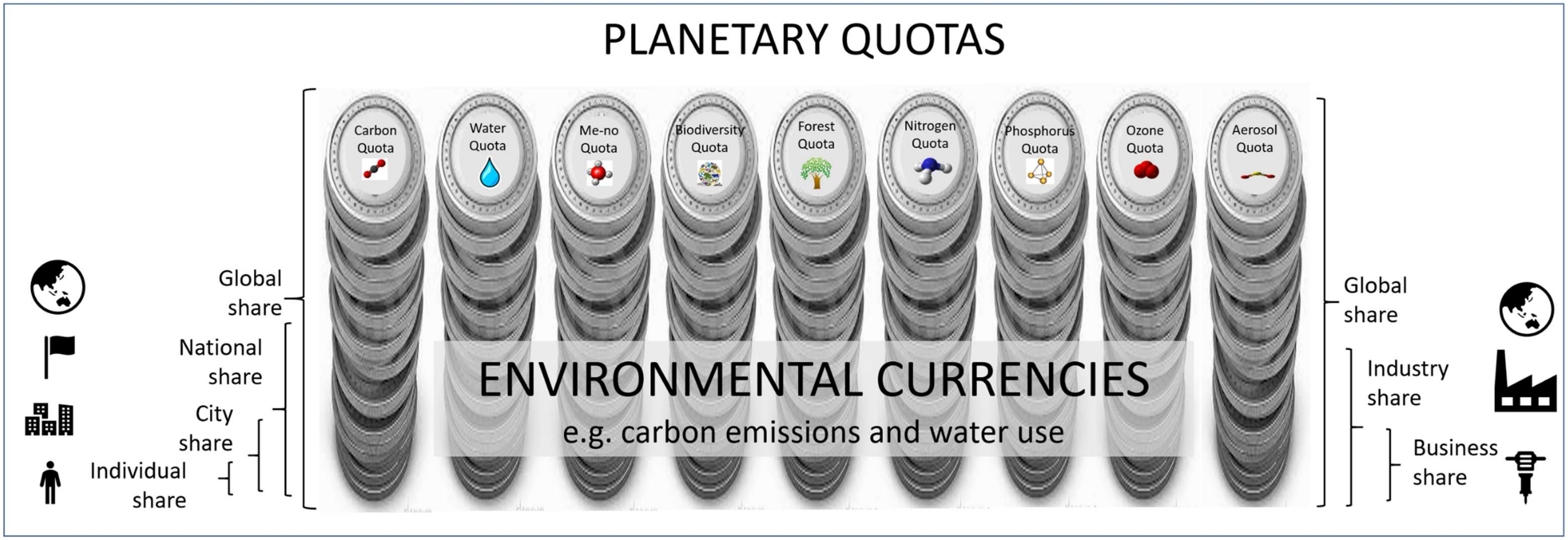

Figure 29: The Planetary Quotas: Scaleable global limits for human induced environmental impacts in environmental currencies such as carbon emissions, reforestation, and water consumption

In order to improve the health of the patient, the doctor might suggest a diet – with maximum calorific intake per day. She might suggest a minimum duration of exercise per day, or an absolute reduction of cigarette consumption to zero. These ongoing guidelines will not instantly fix the patient's health, but over time, his health will improve, and eventually, should return to a healthy benchmark.

The Planetary Boundaries are health checks for the planet. Instead of blood pressure, we measure radiative forcing, instead of weight, we consider atmospheric concentration of CO_2, instead of white cell count, we consider the amount of nitrogen fixated.

The Planetary Quotas are the practical guidelines that allow us to return to a healthy state and maintain this. Instead of calories, there are maximum emissions, instead of exercise, there is reforestation.

Like the exercise and diet, the PQs will not immediately return the planet to the healthy state described by the PBs. However, if followed, we know we are going in the right direction. Moreover, we can predict early on that we are heading towards PB limits that have not yet been exceeded if we are continually exceeding PQs. By continuing to operate within the Quotas humanity can feel confident that we are not pushing the planet beyond its limits.

There is not timeframe assigned to the Planetary Boundaries. There is no pathway of incremental change proposed by the authors. Rather their research defines the end goal. This is intentional. It is up to each person, group, business, or sector to define their own pathways to operate within the PBs. Likewise, the purpose of the PQs is to allow humanity the freedom and flexibility to determine the best way to operate within the safe-operating-space. Where I have had to select a timeframe within which to respect the PBs, notably for the PQs for carbon dioxide and Me-NO, I have chosen the end of this century, i.e., the soonest date considered possible within the academic literature. Of the ten PQs, only the PQ for carbon dioxide has a date at which it must be respected in order for it to remain at the point at which it is currently set. For the remaining PQs, I have not proposed a specific time within which they must be respected. Every year that we exceed them we increase the risk of an irreversible departure from a Holocene-like state of the Earth System. To return to the example of health – an overweight person is at risk of irreversible weight related problems such as heart failure for as long as they are overweight. The sooner they begin to diet, the lower the risk. The inclusion of a timeframe for each PQ should be considered in future work.

It should be noted that unlike for the PBs, no "zone of uncertainty" has been included for the PQs. The zone of uncertainty is included in the Planetary Boundary framework to account for the fact that the science is uncertain. The PQs are intended to show how to operate within the PBs. For this reason, the

PQ limits are set according to the lower limits in the Planetary Boundary framework. Future work should include estimations of uncertainty around the PQ limits.

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 act to try to operate within these; this may never eventuate. The indicators and limits shown in this thesis are intended to be preliminary. It is my intention that, like the Planetary Boundaries, these are subjected to scrutiny, discussion, and analysis, and that they are regularly reviewed and updated over time as we advance in our collective knowledge and understanding.

17.3 The Planetary Accounting Framework

Figure 30 summarises the high level steps that allow the PAF to work for different scales and purposes. The left-hand side shows the inputs and the right-hand side shows the outputs. The inputs are both top-down – scaling the Planetary Quotas to the scale of assessment – and bottom up – using environmental impact assessment methods to estimate impacts in each environmental activity.

A poly-scalar approach was defined in Chapter 3 as one which is

integrative across different scales, sectors, and timeframes, that is not controlled by a single body, but which could be implemented through governance, privatisation, or self-organised management, that is coordinated by a general system of rules which have different mechanisms at different centres of activity.

The diagram shows how the PAF and Planetary Quotas can be used as this general system of rules. The colours show how the PAF addresses each of the core elements that formed the basis of this research:

- Orange: Earth's limits – through the Planetary Quotas – from Chapter 2
- Green: the poly-scalar Earth System management approach – from Chapter 3
- Blue: the environmental accounting system against global limits – from Chapter 4

In addition to these three elements, the yellow boxes show how the PAF has different mechanisms at different scales.

Each box shown in Figure 30 is discussed in the following sections.

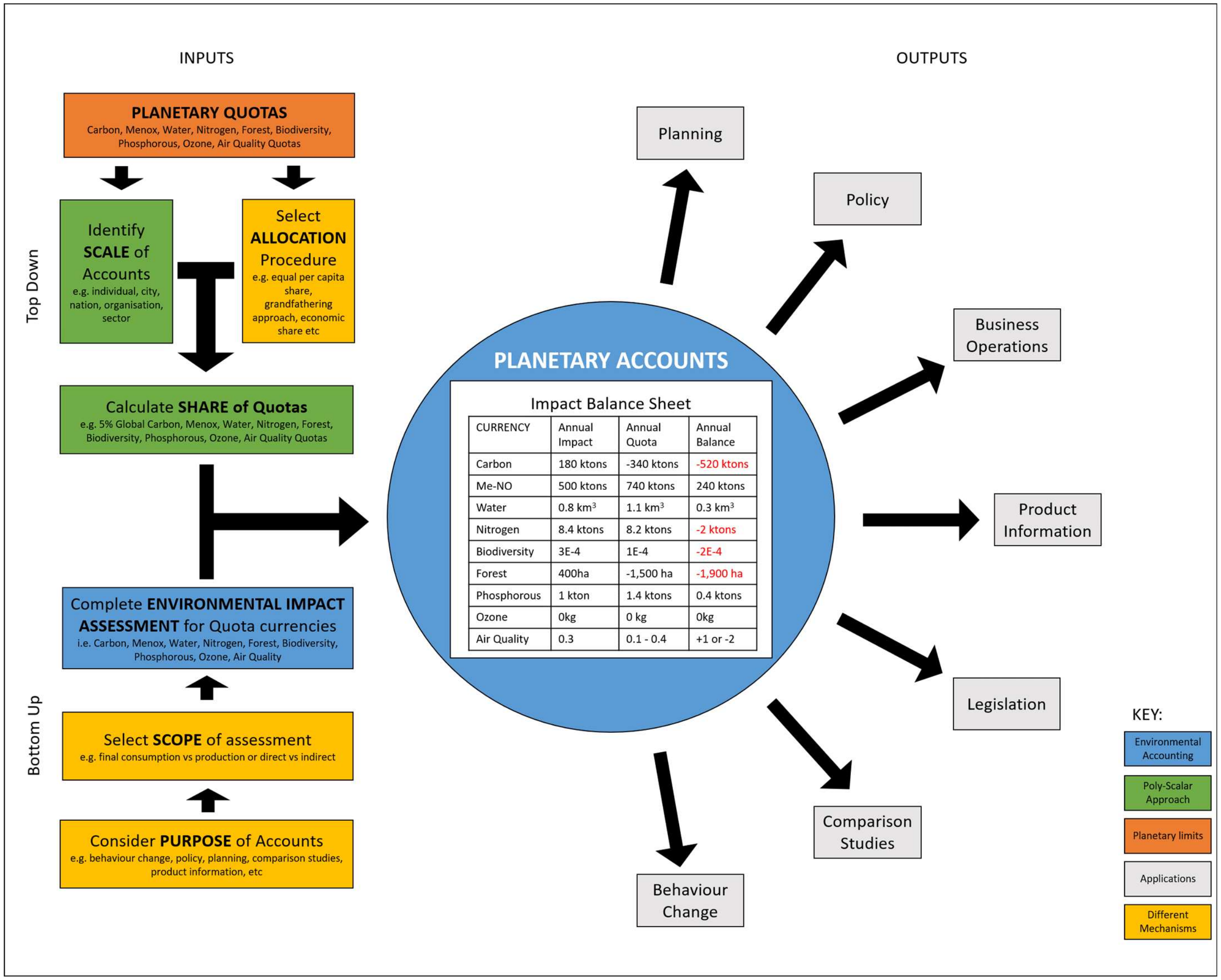

Figure 30: The Planetary Accounting Framework (numbers reported a random sample numbers for visualisation purposes)

17.3.1 Bottom Up

The lower left quadrant of Figure 30 shows the inputs required for the bottom up portion of the accounting procedures. There are three stages in this quadrant: determining the purpose of the accounts, selecting the scope of environmental assessment, and performing the environmental assessment.

17.3.1.1 Purpose

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. Different accounting procedures should be used depending on the purpose of the accounts. For example, a city scale might have several different purposes for which the Planetary Accounting Framework could be used such as the assessment of:

- per capita impacts of the city's inhabitants for comparison with other cities;
- impacts within the city government's jurisdiction to control – to inform local policy and/or planning;
- future impacts under different scenarios – e.g. – the likely impacts after a new public transport system was developped or a new minimum building standard was implemented – to support decision making.

When looking at the per-capita impacts of the inhabitants for comparison with other cities, it would be more relevant to consider the consumption and environmental impacts of each person – whether these occur within the city boundaries or not. For example, the impacts of meat consumed by the city residents should be considered whether the meat was produced within the city boundaries or not. On the other hand, if the city was trying to understand the impacts of infrastructure and activity within their jurisdiction, meat produced outside the city limits would not be relevant and should be excluded from the accounts.

The inclusions and exclusions can make a very big difference to the results. For example, in Sweden the emissions produced within the Swedish borders has reduced from 72.7 $MtCO2_e$ in 1990 to 66.2 $MtCO_2$ in 2010 (Swedish EPA, 2012a). However, when they calculated the emissions corresponding to the consumption of the inhabitants of Sweden, the results were 76 $MtCO_2$ in 1990 and 95 $MtCO_2$ in 2010 (Swedish EPA, 2010). One set of accounts showed a decrease in emissions while the other showed an increase. Both sets of accounts provide information that is useful, but for different purposes. For example, it does not make sense to divide the total emissions produced within the Swedish boarders by the number of inhabitants if the purpose is to understand the behaviour of Swedish people. This would suggest that Swedish people are consuming less and less. This is clearly not the case when we assess the second set of results pertaining to the emissions corresponding to consumption.

The purpose of the accounts must thus be determined prior to defining the scope of assessment.

17.3.1.2 Scope

Scope is a term used in environment impact assessments to describe which impacts are included and which are excluded. The are two key considerations when defining scope for environmental impact assessments.

The first is to determine whether the assessment is *consumption-based* or *production-based* assessments as defined by the purpose above. The inclusions and exclusions are very different between the two. For example, p*roduction* calculations would include all GHG emissions resulting from activities taking place within the jurisdiction under assessment, for example within the city or national borders. In contrast, *consumption* calculations would take into account all GHG emissions associated with the consumption of the people residing in the country or nation – regardless of the location of the emissions themselves. The difference between these two scopes is shown in the example of Sweden's emissions given in Section 17.3.1.1 This type of scope selection is most relevant for scales such as city or national accounts.

The second is to determine the boundaries of influence. This type of scope selection is most relevant for businesses and households. In some instances, it may be reasonable to consider only the impacts under the direct control of the party under assessment. In the example of a households or business this would include electricity and water consumption. In other instances, a broader view is more appropriate. For example, the impacts of the products and or raw materials purchased or used by the business or household. Having a clearly defined purpose for the assessment helps to identify the scope.

It is important that a clearly defined scope is used for any instances where the assessments are going to be compared with one another. Inclusions and exclusions are not necessarily immediately obvious. Take the example of planetary accounts for an individual. Should work-related impacts such as the electricity consumed by an employee's computer be attributed to the employee? To the business owner? To the final consumer of the business output?

Should this differ in the instance that the employee works on a farm or an office? To whom should the impacts of food be attributed? The producer or the consumer?

There is not a right or wrong answer to such questions. The answers will depend heavily on the purpose of the accounts – and there can be many sets of accounts for different purposes. For example, if the purpose of a set of accounts is to compare and evaluate behaviour and consumer choices, then it would make sense to attributed impacts to the final consumer. However, if the purpose is to understand the impacts that an individual can influence, then the impacts that person can influence at their workplace should probably be considered.

As the fundamental premise of planetary accounting is to compare impacts to a share of global limits, it is also important to consider double counting, and missed impacts in the scope definition. If for example, an individual's impacts were to be compared against an equal per capita share of the Planetary Quotas, then one must consider how to deal with public service impacts such as the impacts of healthcare, national security, and local infrastructure. There are any number of ways public service impacts could be dealt with. For example, it could be assumed that 25% of an individual's share of the Quotas would need to be used for public services and the individual's impacts would thus be compared to the remaining 75% of a per capita share. Alternatively, the actual impacts of public services in the individual's region could be determined and a portion of these attributed to the individual.

Appendix 1 gives an example of a scope definition for individual accounts where public service impacts are attributed to the individual. This is intended as an example only. Future work should include the development of formal planetary accounting standards for certain types of accounts, in the same way that there are formal standards for Life Cycle Assessments.

17.3.1.3 Environmental Impact Assessment

The environmental impacts within the defined scope should then be calculated. For example, the emissions of CO_2, the type and amount of land used, the water consumed, and the nitrogen released to the environment would all need to be determined. In the instance that both direct and indirect impacts are included in the scope, the amount of time and cost associated with the data collection for this process is likely to be prohibitive at first. Future work should include the development of basic databases that can be used to access standard impact factors in the absence of more specific data. As more activities are assessed, a wiki-type database could be used to capture this information through crowd sourcing so that the availability of information improves over time (see Box 1). Companies who see value in the concept of planetary accounting may start to disclose this information to consumers. There could even be an opportunity for a *Planetary Facts* labelling scheme in the same way that Nutritional Facts are now mandated on most foods in many countries (this is discussed further in Chapter 18).

Box 17.1: Crowd Sourced Data

I first discovered *mapmyfitness.com*, a health and exercise app, in 2010. The purpose of the app is to track calories eaten against exercise to aid in weight loss. In 2010, when I used the app, the calories in basic foods such as eggs, flour, oil, and vegetables, were embedded within the app. There was some data for specific meals such as lasagne, and for specific brands and products, such as a snickers bar. However, in the absence of data, the user would upload their own. For a home-made meal the app requested the total quantities of each food type to be uploaded, and then the user could select what fraction of the meal they had consumed. For products with nutritional facts labels, there was the option to copy these details in directly. All of the data entered was then stored and made available to any user. A verification process allowed other users to confirm the accuracy of inputs.

In 2017, when I returned to the app to track my calories, almost every meal or product I entered was already available in the apps database. This had all been entered and verified by users – i.e., it had been crowd sourced.

Further work should include the development of environmental assessment standards for planetary accounting. Appendix 2 shows an example calculation of such a procedure for Nitrogen.

17.3.2 Top Down

The upper left quadrant of Figure 30 shows the inputs required for the top-down portion of the accounting procedures. This is the process of scaling the Planetary Quotas from global limits to an appropriate share or allocation.

17.3.2.1 Scale of Accounts

The first information needed is the scale of the accounts. The accounts might be national, for a city or individual, or for a business or sector. The scale of accounts must be understood to calculate the appropriate share of the PQs. The purpose of the accounts will help to determine the scale (see Section 17.3.1.1).

17.3.2.2 Allocation Procedure

The Planetary Quotas resolve the mathematics of apportioning shares of the operating space to different scales of human activity. However, distributing Earth's finite resources among past, present, and future generation is not simply a question of mathematics. It is question of ethics, morals, and beliefs. It is a political debate. If our forefathers used more than their "fair share" of resources, should we be penalised for these decisions? How far should environmental practices alter the lives of people today for the benefit of future generations. Should poor countries, with limited access to basic human rights be allowed to emit fossil fuels to "catch up" when we know that such emissions could push the Earth system into a new paradigm?

I do not attempt to resolve these issues here. This problem is far beyond the scope of my research and expertise. However, Planetary Accounting cannot be practiced without the step of determining a share of the safe-operating space, thus in any Planetary Accounts, some allocation method must be selected. For this reason, an overview of different allocation procedures is given below.

17.3.2.2.1 An overview of different allocation procedures

The concept of apportioning global resources has been most widely researched and debated with respect to the emissions of carbon dioxide (CO_2). It is widely agreed that we should not exceed 1.5°C of average global temperature increase (UNFCCC, 2017). This limit can be translated into a total global "budget" of CO_2 emissions. For example, to have a 90% chance of limiting global warming to 1.5°C total, global, cumulative emissions from 1870 onwards should remain below 555 – 615 GtC[38] (Rogelj et al., 2015). In 2011 we had already emitted 500GtC (Stocker et al., 2013), leaving 55 – 115 GtC to be shared between today's population and future generations.

There are many different theories on who should have the rights to these remaining emissions. Some of the most commonly discussed allocation procedures include:

- Equal per capita share – each person on the planet has an equal right to the remaining allowable carbon emissions
- Equal per capita share with historic accountability – each person who has lived or will live has an equal right to the total cumulative allowable carbon emisisons
- Grandfathering – the rights to carbon emissions are based on a share of carbon emissions taken at a past reference date
- Contraction and Convergence – high users reduce emissions while low users increase emissions until convergence at an equal per capita share level.
- Common but different – rights to the resource based on level of development already achieved

17.3.2.2.2 Equal per Capita Share – A Discussion

Equal per capita share, put simply, means that the global carbon budget is divided by the world population – everyone has the right to the same amount of emissions. This approach was proposed in an early draft of the International Framework Convention (INC, 1991), a revised version of which was accepted at the 1992 Rio Earth Summit (Beckerman and Pasek, 1995). Typically, this amount is then multiplied by each national population and budgets are managed at this level, although there have also been proposals for a personal carbon budget e.g., (Lövbrand and Stripple, 2011).

The main arguments for an equal per capita share are that it is fair - every human being has an equal right to Earth's resources; that it is the only solution that will be widely accepted (Beckerman and Pasek, 1995); that there is no duty to take on obligations resulting in the actions of one's ancestors (Caney, 2013); that there is no international law or precedent that actions with unforeseen, unintended consequences must be mitigated (Beckerman and Pasek, 1995). Moreover, there is no objective way to calculate the costs and benefits of

[38] There is 1kg of carbon in every 3.67kg of carbon dioxide emitted. A budget of 500GtC equates to a 1835GtCO_2.

historic emissions and thus determine the appropriate compensation to or from each nation (Grubb, 1995).

The counter arguments are that since current generations are benefitting and continue to benefit from past emissions, these beneficiaries should bear the burden of the environmental consequences (Shue, 1999). Low-income countries argue that they should not be penalised for historical emissions by high-income countries (Ha and Teng, 2013).

They contend that low-emission countries will be incentivised to make financial gains from the system by selling their “excess” emission rights to high-emission countries who may be unable to make the cuts required to meet their budgets.

The arguments against this method are generally based on historical inequities. The carbon budget is cumulative, and past emissions make up the vast majority of the total. Countries who have emitted more emissions in the past generally have more wealth, better infrastructure, and often a higher quality of life. Countries with low historic emissions are often facing the challenge of aspiring to the level of infrastructure and quality of life experienced in other countries but needing to do so without emitting similar quantities of carbon that were emitted by these wealthier countries.

Further, the global population are already experiencing negative side effects from past emissions. The planet has already warmed almost 1ºC (Stocker et al., 2013). The countries experiencing the brunt of the climate impacts to date are often countries with very low past emissions. They are thus faced with the combined challenge of bearing the costs of climate adaptation and trying to develop without further emissions.

When considering a global carbon budget, the problem is less straight forward. There is a cumulative budget of emissions from 1870 onwards, and in 2017, much of this budget has already been used up (Stocker et al., 2013).

Those who advocate such an allocation argue the lifestyle experienced by those in high-income countries can be largely attributed to past emissions of carbon. Roads, power plants, buildings, and public transport systems take substantial amounts of energy to develop. In countries where this has already been developed, this was almost certainly at the cost of high levels of CO_2 emissions.

Emerging nations such as India and China have aspirations to bring living standards up to the same level as high-income nations but are faced with trying to do so in a time where we understand the importance of limiting carbon emissions.

Not every allocation method makes sense for every Quota. The methods above have been developed for carbon and GHGs for which a total budget over time exists. 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 – thereby altering the frame of the problem. In the example of nitrogen, we have exceeded the Planetary Boundary , and over the past decade we have also exceeded the Planetary Quota each year. However, unlike the Carbon Quota, the Nitrogen Quota is still a positive number, i.e., we do not need to remove nitrogen from the system in order to return to the Planetary Boundary leve – the nitrogen limit is not cumulative. As such, it does not make sense to apply the grandfathering approach in the way that one would for carbon.

This does not mean that the only approach that can work is the equal per capita approach. Rather, that new approaches should be considered and developed based on the different framing that Planetary Accounting provides. It is not necessary that one approach be applied across every Boundary. Some allocation approaches may consider regional differences for Quotas with high regional variability such as the Water Quota. By definition, the basis for the Planetary Accounting framework should have "*different mechanisms at different scales*".

It should be considered that for such a flexible approach, the approach to 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 sectorial approaches to Quotas, may self-select Quotas as part of an internal sustainability strategy, or may be allocated Quotas by local authorities.

17.3.2.3 Calculating a Share of the Planetary Quotas

The Quotas as shown in Table 35 are global limits. Although each Quota is scalable, not every Quota should be scaled by division. The Carbon Quota is an example of a Quota that is divisible – i.e., the global Quota of -7.3 $GtCO_2$/yr could be divided by the global population (say 7.5 billion) to get an equal per capita share of -1 tCO_2/yr per person.

In contrast, the PQ for aerosols does not need to be divided to apply to different scales . The unit (aerosol optical depth equivalent) applies directly at any scale. Thus, the global Planetary Quota, is the same as (for example) any individual's Planetary Quota. Table 37 shows which Quotas are divisible and which are not.

Table 37: Divisible and non-divisible Quotas

Divisible Quotas	Non-Divisible Quotas
Carbon	Air Quality
MeNO	Biodiversity
Forest	
Ozone	
Nitrogen	
Phosphorous	
Water	

The share of the PQs determined can be viewed as an end goal. It is a policy, governance or behavioural decision to determine how quickly the PQs should be met and how to do this. This does not define the pathways.

17.3.3 The Impact Balance Sheet

The results of the environmental impact assessment can then be compared to the scaled PQs in the planetary accounts. An "impact balance statement" can be used show the impact and limit for each PQ currency, and thus the credit or deficit.

17.3.4 Potential Applications

The 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.

17.3.4.1 Planning

Planetary Accounting could be used to assess the relative impacts of different future scenarios. Currently, it is possible to assess the relative impacts of different projects. Results of past environmental impact assessments might be able to tell us that a trainline would reduce carbon impacts by 1000 t/yr and water impacts by 500 m^3/yr compared to new building codes which reduce carbon by 500 t/yr and water by 1000 m^3/yr. The decision makers are then faced with a problem – which is more important. The Planetary Accounting Framework does not include a mechanism to rank different environmental currency. However, with Planetary Accounting these numbers can be put into context of scientific limits. A city-wide impact balance statement might show that the city is doing pretty well against its' PQ for water but has a long way to go to return to its PQ for carbon. As such, the city could make an informed decision to prioritise the train line. On the other hand, a different city might be struggling to meet its' PQ for water, doing well on its' PQ for carbon. In this city the best environmental choice might thus be to amend the building code.

17.3.4.2 Policy

Scaled PQs can be used to determine future science-based targets and to understand the current impacts against these. This information would help to determine specific policies and pathways to reach the targets in a given timeframe. Science-based targets are becoming increasingly popular in the development of policy but are typically limited to carbon, water, and land. The PQs can be used to determine a full suite of science-based targets for critical Earth-system function.

17.3.4.3 Business Operations

The Impact Balance Sheet, and scaled PQs could also be used to inform business operations, sustainability strategies, and long-term planning. The scaled PQs are also useful in risk management. It is widely understood that businesses who emit carbon as part of their core business are at high risk of going out of business. The Quotas will allow businesses to speculate on future risks. For example, nitrogen and phosphorous use are not currently taxed. However, the PBs and PQs show that at a global scale, we are using dangerously high levels of these substances. This suggests that these substances could be taxed or limited in future, information which might flag alarm bells early to allow businesses to begin working on reducing reliance on nitrogen and/or phosphorus before any limits or taxes are put in place.

17.3.4.4 Behaviour Change

The PAF could also be used to develop behaviour change applications, such as a smart phone app which allowed players to compete to reduce their own impacts against their PQs, and to compete against others (this is discussed further in Chapter 18).

17.3.4.5 Comparison Studies

Cities could use consumption-based accounting practices with an agreed scope to compare per capita impacts in different cities across the globe. The results may be very useful for collaborative efforts to reduce impacts. Investigations could be undertaken to understand why some cities have lower impacts than others. The results could help the cities to share ideas and cross pollinate – one of the key benefits of a poly-scalar approach

C40 Cities, a voluntary collective of mayors, is a great example of how this could work. The cities involved are working together to reduce carbon emissions at a city scale. The PAF would allow these efforts to be broadened across critical global variables.

17.3.4.6 Legislation

In the same way that the PAF could be used to inform policy, it could also be used as the basis for environmental legislation at different scales. Common Home of Humanity (CHH) is proposing a new framework for global environmental legislation based on the "condominium model". In a condominium, different units are owned and essentially operated by different parties. However, there are legal frameworks in place to manage the shared systems such as the building envelope, roof, and plumbing and electrical systems. If there is an electrical problem the collective owners have the right to access any part of the system to repair it, even if this access is within a privately-owned space. Likewise, although internal walls where the electrical wires are housed may be privately owned, the owner does not have the legal right to alter or damage the wires as these are collectively owned.

CHH propose that a similar legal construct could be used to manage the Earth System. In the current global model there are mechanisms to legislate in shared territory – the oceans, and outer space. However, many elements that are critical to the overall functioning of the Earth System are located within national territories. The proposed condominium model would give collective rights to such elements. For example, the Amazon Rain Forest is essential to global wellbeing; however, it is currently managed by one nation.

The CHH condominium model plans to use the Planetary Accounting Framework as the scientific basis for the global legislation.

17.3.4.7 Product Information

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 PQs. 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 PQs (such as the water Quota). This is discussed in more detail in Chapter 18.

17.4 Discussion

17.4.1 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.

17.4.2 Comparing Quotas

There is no mechanism to compare one PQ to another or to amalgamate the results of environmental assessments into a single indicator of sustainability. This is intentional. Earth cannot amalgamate environmental currencies such as carbon and water or trade one for another. If humans 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 PQs must be respected if we are to return to and 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 could be used to assign a monetary value to each environmental currency. For example, the costs of adaptation and mitigation of exceeding the PQ for nitrogen could be used to assign a monetary value per 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 (Newman et al., 2017).

17.4.3 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 my 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.

17.4.4 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. 1 kg 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 1 kg consumed or released in one location will have the same impacts as 1 kg 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 kilogram 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.

17.5 Conclusions

This chapter has shown how the Planetary Quotas and Planetary Accounting Framework can be applied in practice to compare impacts of human activity at any scale to scientific global limits.

The subsequent and final chapter concludes this thesis and outlines future work.

CONCLUSIONS

Chapter 18

Conclusions and Further Work

18.1 Introduction

The Planetary Boundaries (PBs) (Steffen et al., 2015, Rockström et al., 2009a) show that we are living beyond the planet's environmental limits. It is apparent that we should aim to return to and live within the PBs. The problem is how to achieve this. The PBs convey important information about Earth system science. However, they do not help to answer the important question of what to do. It is difficult to translate the PBs to action.

The research presented in this thesis shows what is needed to live within the Planetary Boundaries. It uses management theory to support the proposal that a poly-scalar approach to managing the Earth system is needed. It shows that measuring environmental impacts is an essential component of managing these, but that to generate change the impacts must be understood in the context of scientific limits. Moreover, it demonstrates that not all global limits are appropriate for this purpose. For limits to be compared to the impacts of human activity, they must be expressed uniformly in terms of maximum human pressures, i.e., flows to the environment caused by human activity. This thesis establishes that there have not previously been global limits in these terms and shows how new limits for maximum human pressures, the Planetary Quotas, can be derived from the Planetary Boundaries. Finally, it shows how these can be used in practice through the Planetary Accounting Framework.

This concluding chapter shows how the research questions laid out at the beginning of the thesis (see Section 1.2) have been answered. It shows how the research presented here adds to the literature. It discusses the strengths and weaknesses of the research and identifies future work in this area.

18.2 Revisiting the Research Questions

The primary question of this research project was:

How can we connect leading scientific theories of the Earth system and global limits with leading theories of change management and of environmental accounting to develop an implementable system of planetary management?

To answer this primary question, the following secondary questions were identified:

1. Can humans actually change the state of the planet?
2. What is the Earth system science of planetary limits?
3. What is the best way to manage the global environment?
4. How can environmental accounting be used to manage human impacts on the global environment?
5. Why is it difficult to translate the Planetary Boundaries into policy and action?
6. How can these three fields of research, Earth System science, management theory, and environmental accounting practices, be brought together to create scalable environmental quotas that can enable change in human activity?
7. How can environmental quotas be applied in a robust and transparent framework to allow human activity to be managed within the safe operating space of the Planetary Boundaries?

The following sections show how these questions have been addressed.

18.2.1 Can humans actually change the state of the planet?

The premise of this thesis is that humankind should actively manage our environmental impacts to live within the Planetary Boundaries and thus avoid changing the state of the planet. This premise assumes that human activity can and has changed Earth's climate. In acknowledgement that this assumption is not accepted by all, an in-depth review of the scientific literature for and against this theory was conducted.

There are hundreds of arguments made by those who do not believe in anthropogenic (human caused) climate change. It is easy to see why so many people feel uncertain as to what to believe. The task of unravelling every argument made against anthropogenic climate change is immense. Even amongst those who are sceptical about anthropogenic climate change, the basis of their scepticism varies: some simply do not believe the climate is changing, some believe that it is changing but do not believe it is caused by humans, and some do not believe it matters.

The thesis established that the evidence for anthropogenic climate change is compelling (see Section 2.3). There has been a clear warming trend since the industrial revolution (WMO, 2017a, Met Office, 2018, NOAA, 2017, Climate Copernicus, 2017, NASA, 2017). Human emissions are increasing the amount of carbon dioxide and other greenhouse gases in the air, gases known to have a warming effect in the atmosphere (NOAA, 2018b, IPCC, 2013b).

Carbon dioxide and temperature have been closely related for at least 800,000 years (McInnes, 2014) and some correlation between the two can be shown for the past 540 million years (Berner, 1991, Berner and Kothavala, 2001, Crowley and Berner, 2001, Royer et al., 2004). Carbon dioxide levels in the atmosphere are now higher than they have been in the last 800,000 years (IPCC, 2013d). It is extremely likely that human activity, including the emission of carbon dioxide, has caused at least half of the warming recorded since 1950 (IPCC, 2013d).

The results of the investigation into sceptic arguments highlighted that many of the arguments made against anthropogenic climate change are overly simplistic and demonstrate a limited understanding of the complexity of the Earth system (see Section 2.4). For example, some arguments suggest the cooling period from the 1940s, or the hiatus in warming in the early 2000s can be used to disprove the long-term warming trends. This shows a failure to understand how noisy scientific data almost always is. Anomalies in local climates, such as in Antarctica where sea ice is increasing, are cited as evidence against global warming (see Section 2.4.5). Such anomalies simply demonstrate the complexity of the Earth system. Data shows that the average global temperature is increasing irrespective of such regional variations (WMO, 2017a, Met Office, 2018, NOAA, 2017, Climate Copernicus, 2017, NASA, 2017). In a changing climate regional variation is expected (IPCC, 2013b).

Another common set of arguments against anthropogenic warming are based on the identification of past errors either in the data, or in theories proposed to explain data in the past. The premise of such arguments seems to be that in the presence of past errors, the vast amount of evidence supporting the theory can be discounted. Scientists are working to understand the dynamics of an immensely complex system. It is almost a certainty that more errors will be found in past and future data and theories. This is the basis of scientific enquiry. Hypotheses are developed and then evidence is collected to support or disprove these. Methods for collecting and assessing evidence are developed and improve over time. Past incorrect theories such as the 1970s theory of global cooling (see Section 2.4.1) do not constitute evidence against conclusions drawn from long-term temperature data.

This thesis demonstrated that none of the key theories against anthropogenic warming held up against the scientific evidence (see Chapter 2). Further, it showed that based on the scientific evidence available to date, it is extremely likely that humans are causing the climate to warm up and that this is cause for concern. Thus a major PB does appear to have already been exceeded and suggests we must take seriously all the others as well as climate change.

18.2.2 What is the environmental science of planetary limits?

This thesis established that the underlying challenge in determining environmental limits for the planet is that there are no biophysical laws to base these on. The planet has been much hotter and much colder than current day temperatures and it has continued to spin on its axis. Thus, there is a level of value judgement required in determining global limits. For example, to estimate the number of people Earth can support requires assumptions regarding what level of lifestyle those people should have. Some of the assumptions underlying environmental limits can be controversial, which can detract from the purpose of determining them. The debate often becomes about whether the limits are correct, rather than about how we could attempt to live within the limits proposed.

It was argued that the Planetary Boundaries are different (see Chapter 3). The authors of the PBs recognised that the Earth has operated in many different states during human history, and that the state during the Holocene epoch, the period of time which started 11,650 years ago, is the only state during which humanity has thrived (See Section 3.3). They thus set about determining environmental limits that would keep the risk of departure from a Holocene-like state low. This is not to say that the Planetary Boundaries are void of value judgement. For example, the point at which the risk of change is low is often uncertain. However, the argument that humanity should aim for the planet to remain in the only environmental state we know to be favourable to human development is very convincing. The fundamental assumption of the Planetary Boundaries is robust and transparent.

On this basis, the conclusion was drawn that humanity should aim to live within the Planetary Boundaries. However, it was acknowledged that the PBs do not translate easily into policy or action. The research continued to determine what was needed to translate the PBs into a framework that does.

18.2.3 What is the best way to manage the global environment?

It was recognised early in the research that the element missing from the Planetary Boundaries was the connection to policy and behaviour. As such, an investigation of the latest theories of environmental management, behaviour, and change theory was undertaken to determine how best to connect science to management policy to generate change. This research was used to argue that the most effective approach to managing global environmental impacts would be a poly-scalar approach (see Chapter 4). This was defined as one which should:

1. target all *levels* of society from the individual to global;
2. target all *areas* of society including community, business, and governments;
3. be flexible enough to be used for top-down governance, private management, and self-organised initiatives;
4. enable the integration of short-term needs, mid-term goals, and long term visions; and
5. be coordinated by a general system of rules.

It was demonstrated that this idea builds on a previous concept of a poly-centric approach – which is one where many elements make mutual, independent adjustments within a general system of rules (Ostrom et al., 1961, Ostrom, 2009). The concept of a poly-scalar approach advances this idea, by incorporating the need to include not only different scales and management structures, but also to integrate different areas of society and timeframes.

It was concluded that the general system of rules for Earth system management would need to communicate the maximum environmental impacts humans can have in a way that can be used at different scales, across sectors, in different management structures, and over different timescales.

18.2.4 How can environmental accounting be used to manage human impacts on the global environment?

Accounting theory shows that change is driven by the need for limits or standards rather than arbitrary best practice. An analysis of current day environmental accounting practice showed that many nations, cities, and businesses measure and monitor their impacts diligently. Yet, they compare them to arbitrary targets such as past impacts or industry best practice. It was postulated that it is of little relevance that a company achieves best practice standards if best practice impacts will alter the state of the planet.

The importance of measuring and monitoring impacts in order to manage them was established (see Section 5.3.3). However, it was also shown that there is a fundamental limitation in current environmental assessment practices: very few environmental impacts can be understood in the context of scientific limits. This has been highlighted by others as a key limitation for using environmental accounting to inform society of environmental matters (Laurent and Owsianiak, 2017a, Akenji et al., 2016).

The case was made that in order to better manage the global environment, it is necessary to be able to understand critical environmental impacts in the context of global limits, the Planetary Boundaries.

18.2.5 Why is it difficult to translate the Planetary Boundaries into policy and action?

Once it was established that a poly-scalar approach was needed to manage global environmental impacts in the context of the Planetary Boundaries the next task was to determine how. This required an investigation as to why this was not already possible (see Chapter 6).

Two important insights were determined during this investigation. First, the Driver-Pressure-State-Impact-Response (DPSIR) framework was used to demonstrate that for indicators to be actionable, they must be "pressure" indicators, i.e., they must describe flows to the environment. Moreover, it was shown that they must describe flows from human activity, rather than indirect flows between environmental systems.

Second, the DPSIR framework was used to show that the PB indicators are not all in a single category of indicators. Some are pressures (although not all of these are direct pressures from human activity), but most either describe the state of the environment or environmental impacts.

A detailed review of past adaptations of the PBs was used to demonstrate the challenges inherent in scaling or translating state or impact indicators. It was shown that each of them has particular issues with its methodology for scaling limits, and that none of the translated limits respect the Planetary Boundaries (see Section 6.2).

It was thus concluded that a new set of global limits for human activity, based on the PBs, but using pressure indicators was needed, the Planetary Quotas.

18.2.6 How can these three fields of research, Earth-system science, management theory, and environmental-impact assessment, be brought together to create scalable environmental quotas that can enable change in human activity?

The DPSIR framework was used as the basis to translate the Planetary Boundaries into Planetary Quotas. Previous attempts to translate the PBs have dealt with each PB one at a time in isolation. It was apparent from the analysis of past adaptations of the PBs, and from the discoveries made during the literature review of Earth system science and planetary limits, that this sort of approach was flawed. There is a high level of interaction between the PBs. Each of them affects some or all of the others. Much of the integrity of the PBs would thus have been lost in such a linear approach.

To manage this interactivity, a literature review was undertaken to determine the critical pressures pertaining to each of the PBs (Section 7.3.1). Where possible, the pressures were grouped, and then indicators were selected for each pressure or group of pressures (Section 7.3.2). Existing indicators were found to be suitable for most of the pressures or groups. However, in order to consistently translate the Planetary Boundaries into pressure indicators, a new indicator for aerosols was developed (see Chapter 12).

Many of the critical pressures for the different PBs overlap. This meant that most of the indicators could be traced back to more than one of the Planetary Boundaries. A limit was determined for each indicator at the point where each of the corresponding PBs would be respected.

An extended peer community engagement was used to enhance the validity of the Planetary Quotas and the way these could be applied (see Section 7.3.3). This entailed twelve months of visiting global experts to engage them in the review and refinement of the proposed indicators and limits, and in the framework discussed in the next section. Experts in the fields of aerosols, climate change, water, nitrogen, biodiversity, and land-use were consulted regarding the relevant Planetary Quotas. Six of the authors of the Planetary Boundaries were engaged to gain an in-depth understanding of the unpublished background of the Planetary Boundaries, and to get their high-level insights as to the strengths and limitations of the Planetary Quota approach. I presented at conferences with a focus on the social sciences to obtain feedback on the system from this perspective. I partnered with the World Resource Institute and World Business Council for Sustainable Development to run a workshop on creating credible metrics for business to gain a business perspective.

The insights gained during the extended peer community engagement shaped the project from the specifics of some Planetary Quotas, to a broadened understanding of how these might be used in practice.

18.2.7 How can environmental quotas be applied in a robust and transparent framework to allow human activity to be managed within the safe operating space of the planetary boundaries

The purpose of the Planetary Quotas was to translate the Planetary Boundaries into limits that could be applied to human activity through a poly-scalar approach. One of the fundamental requirements for a poly-scalar approach is a general system of rules. The PQs are limits. They do not constitute a system of rules. As such, a high-level Planetary Accounting Framework was developed. The development of the PAF was done through integrative thinking, critical evaluation, and extended community engagement (see Chapter 7). The underlying concept is that environmental accounting, the measuring and monitoring of environmental impacts, can be advanced to planetary accounting, the comparison of these impacts to global limits. The Planetary Accounting Framework outlines how this can be done in a poly-scalar way. It provides mechanisms to enable a flexible approach so that different sectors, management structures, temporal elements, and scales can all be addressed (see Section 17.3).

18.2.8 How can we connect leading scientific theories of the Earth system and global limits with leading theories of change management and of environmental accounting to develop an implementable system of planetary management?

This thesis has shown that the Planetary Quotas and the Planetary Accounting Framework can be used to bring together leading scientific theories of planetary limits, the social science of change, and environmental accounting in an implementable system of poly-scalar Earth System management within the Planetary Boundaries.

The research presented here adds to the literature in a number of ways. It extends the concept of a poly-centric approach to a poly-scalar approach using findings from behaviour and change theories (Ostrom, 2009, Eon et al., 2017, Eon et al., 2018) (Eon et al., 2017) (Steg and Vlek, 2009) (Steg, 2016) (Newman, 2005) (Kaufman, 2009). It begins to address previously identified limitations of environmental accounting (Akenji et al., 2016, Fang et al., 2014) by connecting key impacts to global limits going beyond (Ewing et al., 2010a, ISO, 1997, Fang et al., 2015a). It adds to the field of Earth system science by developing scientific global limits in pressure indicators unlike (WBGU, 1995) (Ekins et al., 2003, Rockström et al., 2009a, Steffen et al., 2015). It uses insights derived from the DPSIR framework to determine why the Planetary Boundaries are not accessible or actionable going beyond (Dao et al., 2015, Nykvist et al., 2013). Finally, it enables the operationalisation of the Planetary Boundaries, by connecting these fields through Planetary Quotas and the Planetary Accounting Framework and sets out how this can be done.

18.3 Strengths and Weaknesses

The strength of this research lies in its combination of management theory, environmental accounting, and Earth system science. Drawing on these fields allowed it to present a framework for evaluating environmental impact which was both scientifically rigorous and actionable. Previous research in this field (Rockström et al., 2009d, Steffen et al., 2015, Sandin et al., 2015, Fang et al., 2015a, Dao et al., 2015, Nykvist et al., 2013, Ewing et al., 2010a) has been either scientifically rigorous or actionable, but not both.

A key element of this research was the identification of the importance of the type of indicator selected for policy applications. This insight has been identified by practitioners in the past. Yet it does not seem to have made its way to the field of Earth system science. It is likely that the specifics of the Planetary Quotas may change once made available to the scientific community to asses and develop. However, the fundamental premise, that limits must be communicated in pressure indicators, should not.

One of the strengths and weaknesses of the thesis is in its breadth. The task of connecting three previously unconnected fields of research and deriving Planetary Quotas across nine different fields of science would be a daunting task for a multi-disciplinary team. To attempt this as one PhD student with a background in engineering and sustainable building design was overwhelming to say the least and could not have been possible without the help of many scientists who were able to explain their work and followed me down the track of delivering a pressure indicator for the PBs. The multi-disciplinary aspect of the work can be considered a strength. The research connects science with policy and business. As shown in this thesis, this is a gap that needs to be addressed if we are go generate the magnitude of change needed. A weakness is that it was not undertaken by a multi-disciplinary team who would likely have had additional insights that could not be determined without depth in each field. The extended peer community engagement was undertaken to address this weakness as far as possible possible and indeed the scientific aspects of translating PBs into PQs was probably sufficiently rigorous due to the remarkable access to so many global leaders in this field. However, without time or budget, there were limits as to the involvement of other experts who could have been engaged in the process of creating actionable indicators. Perhaps other specialists in poly-scalar change management would have come up with a better approach and time will tell if this now can happen.

The high-level PAF outlines key steps that would apply to any level of application of the framework. Each of these steps will need to be developed to give a more detailed PAF or perhaps several PAFs (for example to address the differences between applications for individuals, businesses, governments, products, etc.)

Another limitation of the system presented in this thesis is that it has not yet been applied and evaluated as an instrument to guide policy, business, or behavioural decisions. In the development of the concept, and particularly of the framework, much effort was taken to envision the different applications to determine and address potential weaknesses of the system. However, there is no substitute for real world applications. Once a more detailed PAF has been developed, the next step will be to apply and test the framework under different scenarios.

The ten indicators selected for the Planetary Quotas vary in their robustness, and in the likely availability of quality data. The indicator for the PQ for carbon is already widely used which means that it is likely to be quite robust with plenty of data. In contrast, the indicator selected for the PQ for biodiversity is relatively new and the indicator for the PQ for aerosols was developed as part of this thesis. These indicators will need to undergo substantial testing in different applications to assess their robustness. It is likely that the data needed to measure impacts against these indicators is difficult to find at first.

18.4 Future work

The Planetary Quotas and Planetary Accounting Framework were developed as a way to manage human impacts on the environment to return to the safe operating space defined by the Planetary Boundaries. There is much work to be done for this to become a reality.

Each of the Planetary Quotas should be reviewed and revised as needed by the scientific community. This should not be a one-off occurrence. Rather, this should happen on an ongoing basis, so that the limits reflect the latest scientific knowledge.

The high level PAF should be further developed. The System of Environmental and Economic Accounting Central Framework (SEEA-CF) should be used to inform this development to align the framework ith international environmental reporting standards.

One of the weaknesses of the project identified above is that it has not yet been tested. This will be an important next step in the further development and refinement of both the PQs and the PAF. Projects should be undertaken in the community, with industrial partners, and at different levels of government, for example a local area, a city, and a national government. These projects should not be done in isolation with one another. The specific application of the framework is likely to vary between sectors. However, the findings from each project, both positive and negative, should be recorded and shared. A sound approach for evaluating applications should be determined. This will enable rapid development and enhancement of the system.

Further research should be undertaken to determine how best to communicate the PQs and PAF to the wider population. Feedback from the extended peer community engagement has already included the opinion that the nomenclature and scientific units used for the PQs is still too complex for the general public. This may be simply improved by people involved in the next phase of application.

There is work underway to develop a legal framework for the Earth system, which would use the PAF as the scientific basis (see Section 17.3.4). This proposal is promising. However, more research should be undertaken to determine whether there are also other legal frameworks, governance structures, community engagement initiatives, or business drivers that could help to generate global change using a PQ approach.

One of the key benefits established for a poly-scalar approach to global environmental management is that it would enable trial and error of different solutions at different scales and under different circumstance. Findings from such varied approaches could help to accelerate change. However, this is only true where the lessons can be captured and shared. Research should be done to determine whether this could be possible through an online platform using means such as crowd sourcing. This has been done successfully to gather data in the past (see Box 17.1 for an example).

The research presented in this thesis has also highlighted areas of future work for the PBs. As identified in this thesis, the PBs are not in a uniform category of indicator. Some are pressures, some states, and one is an impact (see Section 6.3). The role of the PBs is to assess and communicate planetary health. This is best done through state and impact indicators. Where the PB indicators are pressures, for example water consumption, nitrogen fixation, or phosphorous release to the oceans, the health of the planet with respect to these processes is not well communicated. In the same way that the PBs using state and impact indicators could be translated to pressure indicators, it would be possible to translate the PBs which are in pressure indicators to states or impacts. For example, the PB for water consumption could be translated to an indicator such as the percentage of water bodies experiencing water scarcity, nitrogen and phosphorus indicators could be translated to global area of aquatic dead zones.

Thus far, the PB have been developed by a self-selected group of scientists. However, there is talk of developing an independent committee tasked with the ongoing management and updating of the PBs. If this was to occur, the same committee could also be tasked with linking these PBs to PQs in an ongoing manner. A full suite of state and impact Boundaries, with a full suite of pressure Quotas, that were maintained by an independent scientific body, would be a powerful tool for Earth system management. It is not hard to imagine how such a group could generate a global research and policy process similar to that developed by the IPCC for climate change. This process is led by several thousand scientists sharing their findings with policy makers in an on-going dialogue. The processes that began through the IPCC have created significant change (Newman et al., 2017) though much still needs to be done. Such a process could now be shifted to include the Planetary Boundaries and show the synergies and trade-offs that could be created by bringing all the PQs together into a PAF that is constantly being updated and demonstrated.

There are three further specific applications of the PAF that I personally hope to see implemented. The first is the derivation of economic value of key environmental impacts, using the PQ "currencies". The second is the gamification of the PAF in a smart phone application. The third is a "planetary facts" labelling system for products and services. These three ideas are expanded below.

18.4.1 Economic Value

Scientists can estimate the cost of mitigating and adapting to environmental degradation. For example, there have been estimates of the social cost of CO_2 which range from USD$12 – 64 per tonne (IWGSCC, 2013). This cost is based on future damages avoided derived from predicted costs from impacts such as sea level rise, changes in agricultural yields and ecosystem function. There is a high degree of uncertainty in such estimations. However, assigning costs to environmental impacts begins to communicate the importance of these in a global language. Further work should include the continued development of social cost estimates for environmental currencies, and the estimation of the true value of each of the PQ currencies, per unit of impact.

Major polluters would need to pay the true costs associated with their impacts and these would be carried over to consumers of such impacts. Countries with environmental assets critical to Earth system functioning could be financially incentivised to maintain these. It could form the basis of initiatives such as a globally capped impact trading scheme which could happen at any scale of activity across all of the PQ currencies. The inclusion of environmental impacts into the existing economic structures would constitute systemic change. and show how the growth in each PQ can be decoupled from growth in wealth as is happening with greenhouse emissions (Newman, 2017b).

18.4.2 Gamification of the PAF

There are several personal impact calculators available online e.g., (Global Footprint Network, 2018) (WWF, 2918) (Anthesis, 2014) (n-print, 2012) (Water Footprint Network, 2018). These allow users to calculate their impacts such as their ecological, water, nitrogen, or carbon footprints. There has been rapid growth in the number of online personal impact (PI) calculators over recent years suggesting increased interest in personal sustainability (Franz and Papyrakis, 2011).

The purpose of these calculators is to educate players and encourage behaviour change to reduce impacts (Franz and Papyrakis, 2011). However, a review of popular online calculators shows that most calculators:

- propose limits that are not based on scientific planetary limits; or
- do not propose limits at all;
- where limits are proposed, many do not provide options which allow players to win i.e., even when the best options are selected, the impacts shown exceed the proposed limits;
- are based on average per capita national production impacts i.e., the data is skewed to show higher impacts for people living in countries which are net exporters than for people in net importing countries;
- use generic impacts/$ to estimate impacts of goods and services.

The result can be that players are left with a sense of confusion and/or doom (see Figure 31). Most online PI calculators do not encourage behaviour change.

The PAF could be used as the basis to advance personal-impact calculator and develop a “real-life” game. The PAF and PQs could be used as the basis for the impacts assessed and end goal targets proposed. Engagement with game developers would be needed to determine the best way to design the game to generate a high uptake of users. Further research would be required to determine the most effective ways to generate change through games. The idea of using games to change behaviour has proven successful in the past. For example, SPARX (Smart, Positive, Active, Realistic, X-factor thoughts) is a game which has been shown to reduce teenage depression scores as successfully as cognitive behavioural therapy delivered by a qualified psychologist (Merry et al., 2012).

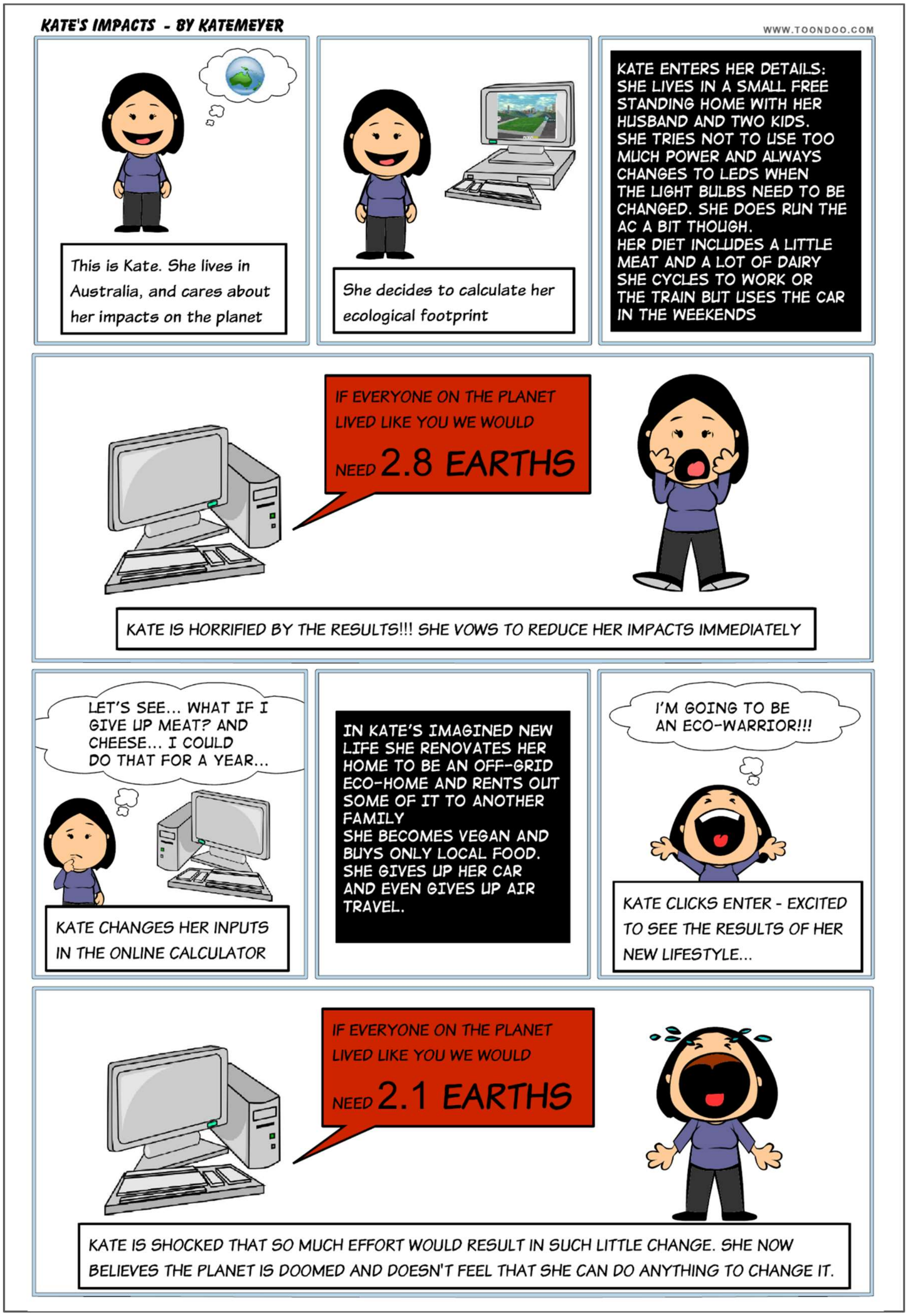

Figure 31: A cartoon depiction of the failure of many online personal impact calculators to achieve their fundamental - to improve individual behaviour

18.4.3 Planetary Facts Labelling

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 PQ (see Figure 32). Whether this was displayed on products as depicted or made available in some other way would need to be determined. Irrespective, the communication of the impacts in each PQ currency and the proportion of a recommended PQ that comprises would enable consumers to begin to understand the impacts of their purchasing decisions in the context of global limits. This is fundamentally different from existing labelling schemes which typically provide information about impacts compared to industry benchmarks.

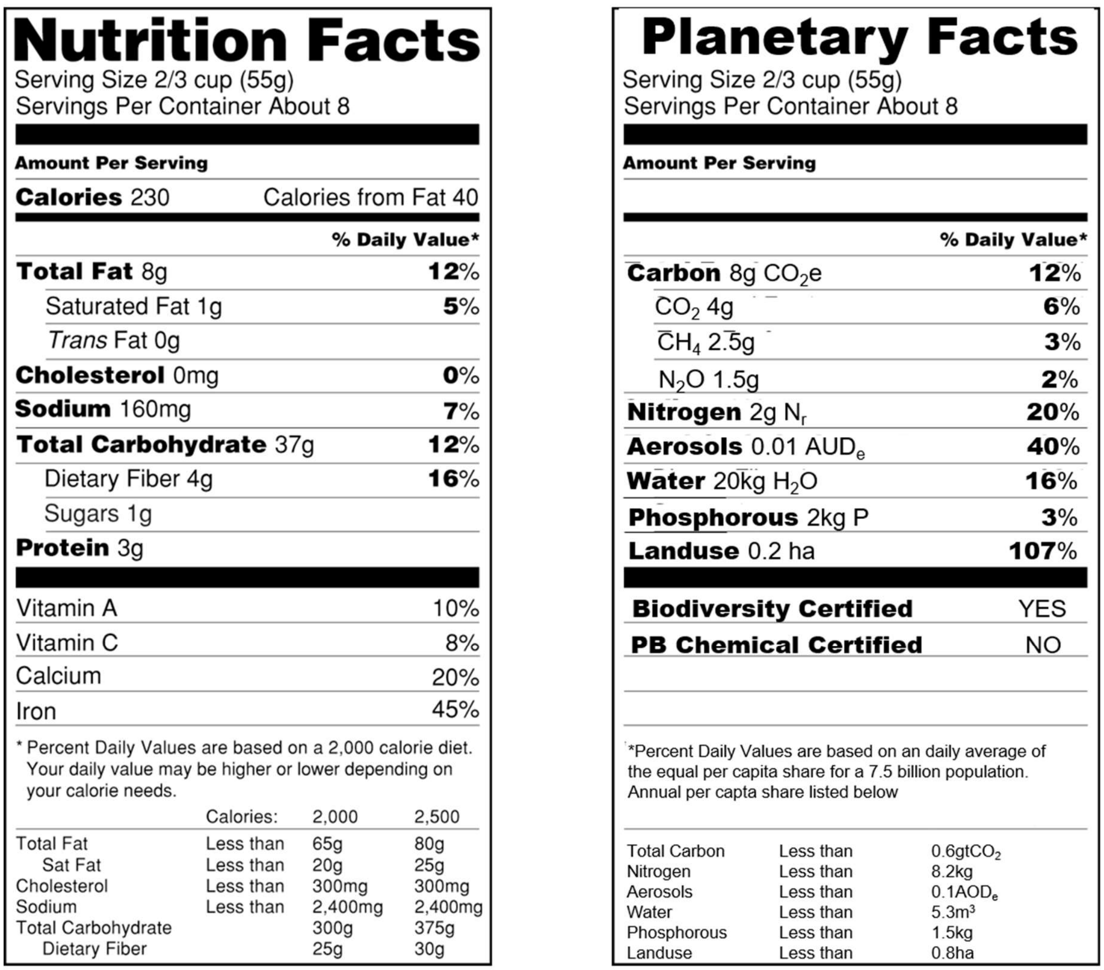

Figure 32: Planetary Facts labels could give consumers information in the same way that nutrition facts tell consumers what is in their food

18.5 Concluding Remarks

Generating change to live within planetary limits is more difficult than simply knowing what these limits are. It is necessary to understand how people behave and what drives people to make certain choices. Further, one must consider current environmental management practices and the advantages and limitations of these. To generate serious change so that we can live within the planet's environmental limits requires integrative thinking that brings together the scientific knowledge of Earth's limits, the utility of environmental impact assessment frameworks, and the understanding of behaviour, change, and management theories. The thesis has begun to show how this can be done. The research presented in this thesis shows how the Planetary Boundaries can be translated into Planetary Quotas and the Planetary Accounting Framework to make global environmental limits accessible and actionable to all scales of human activity. This approach could form the basis for the management of the Earth system to help us to return to and live within the Planetary Boundaries.

APPENDICES

Appendix 1

Example of Scope Definition for Individual Accounts

This Appendix is intended to give an example of scope definition for the Planetary Accounting Framework and some of the decisions that would need to be addressed consistently in order for the results of different accounts to be compared. The example given is for individual accounts which are to be compared to a per capita share of the Planetary Quotas. In this example, regional public service impacts are determined, and an equal per capita share assigned to each resident of the region.

Note – this scope definition has not been developed as a proposal, but to demonstrate the level of detail and the sorts of decision making frameworks that would be required to formally define the scope of a given set of accounts.

General:

Individual impacts are based on final consumption. All impacts which occur due to human activity must be allocated to a single person with no double counting. Where there is consumption by one person of something owned by another person, the impacts are assigned to the user rather than the owner, regardless of who caused the impacts. I.e. If impacts are caused by Person X (or assets owned by Person X) but contribute to a product/process/service to be consumed by Person Y they are allocated to Person Y.

Examples:

Person Y lives in a house owned by Person X.

> *Electricity, water, gas consumed in the house is allocated to Person Y (and any other occupants).*
>
> *Person X decides to put photo voltaic panels on the roof. Any embodied impacts from the panels, and any reduced impacts from the renewable energy, are allocated to Person Y.*
>
> *Person X plants new trees in the garden. Any impacts from the gardening (e.g. fuel for delivery of the tree, fertiliser etc) and any impact reductions (carbon uptakes) are allocated to Person Y.*

Public/Government Services (e.g. healthcare, education, roads) are allocated evenly to all residents of the service catchment as applicable. I.e. If Service A is used by Person X, Person X accounts for:

Total Public Service A Impacts / Total Residents Served by Public Service A

Examples:

Person X is very healthy and has never been to hospital, however there is a public health system where they reside. There are N residents served by the public health system in question. Each year, Person X accounts for

Total Annual Impacts$_{healthcaresystem}$ */ N Users.*

Person Y chooses not to attend public school, and rather goes to a private school nearby. Person Y still accounts for their proportion of the public school impacts. However, Person Z will also account for a share of the impacts at the private school.

Person A lives in country Y where there is a great public healthcare system. However Person A does not have the right to use it. Person A still accounts for a share of the impacts of the public healthcare system where they reside.

Private Services (e.g. healthcare, accountancy, law) and other Shared Impacts are accounted for via the best available allocation procedure as follows:

a) A physical division – e.g. hours of accountancy services, kg of product, m^2 of area
b) A monetary division where physical division is not possible – e.g. Money Spent by Person X on Service A/Total Income for Service Provider A

Examples

Person X is an avid golf player. Impacts of the golf course are allocated based on hours of golf played. Person X accounts for:

Total Impacts of Golf Course x (Hours Played by Person X / Total Hours Played at Golf Course)

Embodied Impacts of Products and Services are allocated differently depending on frequency of typical purchase of the product type. Embodied impacts of products/services purchased frequently (e.g. food) are accounted for at the time of purchase. For products purchased infrequently (e.g. cars, houses), the embodied impacts are allocated over a typical lifetime as follows :

$EI_y = (2EI_{tot} / L^2)Y \times (2EI_{tot}/L)$

Where :

EI_y = Embodied Impacts for year y

EI_{tot} = total embodied impacts

Y = years since purchase (year of purchase = 1)

L = life expectancy

Where it is unclear which category a product should be allocated (e.g. clothes, computers, furniture), it is at the discretion of the user to choose one or other accounting system. This does not need to be consistent from one item to another, but must be consistent from one year to another and from one person to another (for multiple owners) for any given item.

Examples:

Person X purchases new jeans, accounts for the embodied impacts at the time of purchase, and sells them to Person Y. Person Y does not need to accounts for any embodied impacts (regardless of extent of use by Person X/Person Y).

Person X purchases a new laptop and accounts for the embodied impacts via depreciation and then before the life expectancy of a laptop, sells/rents/gives the laptop to Person Y. Person X accounts for the annual embodied impacts each year until the transfer to Person Y, then Person Y accounts for the annual embodied impacts hence forth.

Person X purchases a new jacket, does not use it, accounts for embodied impacts via depreciation and then before the life expectancy of a jacket, discards it. Person X accounts for all remaining embodied impacts the year of discard.

Person X purchases a house and lives in it for less than the life expectance of a house, then sells OR RENTS to Person Y, Person X accounts for the annual embodied impacts each year of residence, then Person Y accounts for the annual embodied impacts hence forth.

Person X lives in a house that is older than the life expectancy of a house. Person X does not need to account for embodied impacts.

End of life impacts are accounted for at the time of disposal and attributed to the last owner. If material(s) in the product are reused or recycled then end of life impacts are limited to any impacts associated with deconstructing the product (if required). Impacts associated with the transportation to the recycling plant and reprocessing of the material are accounted for as embodied impacts of the subsequent material use. If material is sent to landfill then full ongoing impacts of the product are accounted for at this stage. If the material is sent to landfill and used for energy – the proportion of material converted to energy (based on efficiency) is allocated to the energy stream and not to end of life.

End of life impacts are an exception to the user vs owner rule. End of life impacts are attributed to the owner but can optionally be redistributed between owner and user upon agreement by all parties.

Examples:

> *Person X owns a property and demolishes it. The timber in the home is salvaged, but all other materials are sent to landfill. Person X accounts for all impacts associated with the demolition, including those associated with efforts to extract the timber. Person X accounts for all landfill impacts, including transport to landfill impacts. Person X does not need to account for transport of the timber from the site or any further impacts of the timber.*
>
> *Person X owns a car but Person Y uses. The car dies and needs to be disposed of. Person X and Person Y agree that the end of life impacts will be accounted for by Person Y.*
>
> *Person X sends all of his waste to Landfill A. Landfill A is a waste to power landfill with a conversion efficiency of 20%. Person X accounts for 80% of the end of life impacts of his waste.*

Appendix 2

Example Calculation - Nitrogen

18.6 Nitrogen Footprint

Nitrogen is released to the environment through the production of plants and animals and the combustion of fossil fuels. Diet is the greatest contributor to the release of reactive nitrogen to the environment due to human activity, however other human activities also contribute(Leach et al., 2012).

The N-Calculator includes Food, Housing, Transportation, and Goods & Services (n-print, 2011).

Food

Nitrogen Footprint from food is calculated in two stages. Nitrogen used to produce the food and the nitrogen released from the food as waste (after consumption or as waste).

N-print calculates average per capita food consumption and then modifies the average figure using personal inputs for the personal footprint calculations. They take data from FAO on foods consumed and the corresponding protein supply. Nitrogen consumed is calculated using 16% of protein by mass. As adults do not accumulate nitrogen it is therefore assumed that ALL nitrogen consumed is excreted and released to the environment. However there are existing advanced sewage treatments which can denitrify about 90% of reactive nitrogen in human waste (Gorecki and Melcer, 2006). This means that nitrogen should actually be calculated as three elements:

1. Nitrogen released to the environment during the production of food
2. Nitrogen released to the environment after consumption of food
3. Nitrogen released to the environment from wasted food

Nitrogen released during production:

N-print developed virtual N Factors for use in the calculation of Nitrogen Footprints. These are given in the table below. Any food produced that is not specifically covered by these N Factors used the N Factor of the food group with the most similar production process.

Table 2
Virtual N Factors.

Food category	Virtual N Factor
Animal products	
Poultry	3.4
Pigmeat	4.7
Beef	8.5
Fish and seafood	3.0
Milk	5.7
Vegetable products	
Vegetables	10.6
Starchy roots	1.5
Legumes	0.7
Grains	1.4

Where there is no detailed information provided, we propose that these factors are used to calculate the Nitrogen Footprint at any scale. However, we propose that a product labelling system should include actual nitrogen released to the environment for each food item (as well as non-food products) which should be used in preference to these figures where available.

Nitrogen released after consumption:

Nitrogen released after consumption is calculated as 16% of protein consumed – percentage of nitrogen removed during sewage treatment. This can be calculated at any scale. At an individual or precinct scale the sewage treatment will be the actual treatment in the calculation of True Impacts and global average treatment in the calculation of Theoretical Impacts. I.e. If 10% of global sewage is treated to remove 90% of nitrogen then the theoretical impacts will be calculated as:

16% of protein consumed – 9% (90% x 10%)

Nitrogen released from wasted food:

In the personal footprint calculations, the nitrogen footprint of food wasted is calculated as 16% of protein purchased and not consumed.

At a precinct, city, or national scale, the nitrogen footprint of food wasted is calculated as 16% of the protein produced and not sold, PLUS 16% of the protein imported and not sold.

At a global scale the nitrogen footprint of food wasted is calculated as 16% of protein produced and not consumed.

Transport, Housing, Goods and Services

For the remaining categories, all nitrogen footprints are general made up of three components:

1. Direct fossil fuel consumption
2. Embodied fossil fuel consumption
3. Non-fossil fuel embodied nitrogen released in the production of raw materials

In the calculation of impacts at a personal or precinct level, this is done from the bottom up based on actual consumption/use as detailed below. At a city, regional or national level, this can be done from the top down based on total use of fossil fuels and nitrogen. For production based calculations this will include all fossil fuel combusted and nitrogen used within the boundary. For consumption based calculations this will include all fossil fuel combusted and nitrogen used, minus exports, plus imports. At city, regional and national levels it would still be of value to categorise the nitrogen impacts into these categories to enable appropriate decision making to reduce nitrogen impacts.

Transport

The nitrogen footprint of transport is calculated as:

nitrogen impacts of fossil fuel consumption per km travelled

plus

embodied nitrogen impacts of the transport mode

Where the transport system is owned/controlled by the entity, the full embodied impacts of the system are allocated to the entity depreciated linearly over the expected life of the system. E.g. If a person owns a car, they will account for the embodied nitrogen of the car each year following the formula:

<Insert formula>

Where the system is not owned/controlled by the entity (e.g. a person is calculating the impacts of using the train) the person will account for their proportion of use based on the predicted annual use. I.e. for True Impacts, if the person travels X person km by train and the trains are expected to be used a total of Y person kms the person will account for X/Y x annual embodied impacts of the trains. For theoretical impacts, an average person km figure will be applied for train travel.

Housing

At a personal and precinct level, the nitrogen footprint of housing can be calculated as:

Fossil fuel consumption at the home

Fossil fuel consumption due to electricity consumed at the home

Embodied energy of the home

At a city/regional level the nitrogen footprint of fossil fuels is calculated directly but can be classified as housing, transport, etc.

Goods and Services

The nitrogen impacts of goods and services has typically done through environmental input output analysis which assigns a dollar value to goods and services. However in the interest of decoupling economics and impacts, we propose an alternative approach.

As per the virtual N-Factors associated with food types, we propose the development of virtual N-Factors for all goods and services. We propose the development of a certification scheme which then allows goods and service providers to disclose actual nitrogen data for their products and services. Where no data is provided, the virtual N-Factors will be used.

Appendix 3

Glossary of Terms and Abbreviations

3.1 Glossary of Terms

Dobson units	A measure of the amount of a gas in a vertical column of atmosphere
DPSIR Framework	European Environment Agency framework for categorizing indicators as Drivers (human needs, such as the need for fuel), Pressures (flows to the environment, such as CO_2 emissions), States (describing the state of the environment, such as the concentration of CO_2 in the atmosphere), or Impacts (describing a change in State, such as global warming).
Driver indicator	An environmental indicator which describes a human need such as the need for fuel, transport, or electricity
Environmental Footprints	The amount of impact an activity, person, or group (often a nation) has on the environment. These are often measured in land area but can also be measured in other units such as mass or volume.
Earth system	The sum of the planet's physical, chemical, and biological processes.
Earth-system processes	Physical, chemical, and biological processes such as the carbon cycle
Holocene-like state	The state of the environment during the Holocene epoch, and the only state in which we know settled human societies can thrive.
Holocene	The geological period of time which began 11,650 years ago
Impact indicators	Environmental indicators which describe impacts, such as change in global average temperatures

Planetary Accounting Framework	A new tool for environmental management that allows the environmental impacts of any scale of human activity to be understood in terms of the Planetary Boundaries
Planetary Boundaries	A formal framework that sets out nine global environmental limits.
Planetary Quotas	A set of global limits for human activity which show what is needed to live within the Planetary Boundaries.
Pressure indicator	An environmental indicator which describes a flow to the environment. For example, carbon dioxide emissions or chemical flows to waterbodies.
Safe operating space	The space defined by the Planetary Boundaries collectively
State indicator	An environmental indicator which describes the state of the environment. For example, the concentration of carbon dioxide in the atmosphere or the species richness of an ecosystem.
Threshold	The point at which an Earth system process is likely to undergo non-linear change – for example abrupt retreat of sea ice caused by global warming

3.2 List of Acronyms

CPD	Convention on Biological Diversity
DALY	Disability-adjusted life years
DPSIR	Driver Pressure State Impact Response
EF	Ecological Footprint
GDP	Gross Domestic Produce
IPAT	Impact = Population x Affluence x Technology
IPCC	International Panel for Climate Change
ODP	Ozone Depleting Potential

ODS	Ozone Depleting Substance
PBs	Planetary Boundaries
PM	Particulate matter
PMC	Particulate matter concentration
PPM	parts per million
PPB	parts per billion
UV	ultra violet

3.3 List of Chemical Formulae

CH_4	Methane
CO_2	Carbon dioxide
O_3	Ozone
N	Nitrogen
N_2O	Nitrous Oxide

3.4 List of Units

Gt	giga tonnes
ha	hectare
km^2	square kilometres
M	million
Ma	million annum
Mha	Million hectares
Mt	mega tonnes
nm	nanometres
ppb	parts (of the substance) per billion parts (of atmosphere)
ppm	parts (of the substance) per million parts (of atmosphere)
ODPt	Ozone depleting tonnes

t	tonnes
W/m^2	Watts per square metre
yr	year
$\mu g/m^3$	micrograms per cubic metre
µm	micrometre

3.5 List of IPCC confidence intervals

The terms used to describe likelihood correspond to scientific probabilities as follows:

"virtually certain"	>99%
"extremely likely"	>95%
"very likely"	>90%
"likely"	>66%
"more likely than not"	>50%
"very unlikely"	<10%

The term "very high confidence" conveys a 9/10 chance of being correct.

Appendix 4

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