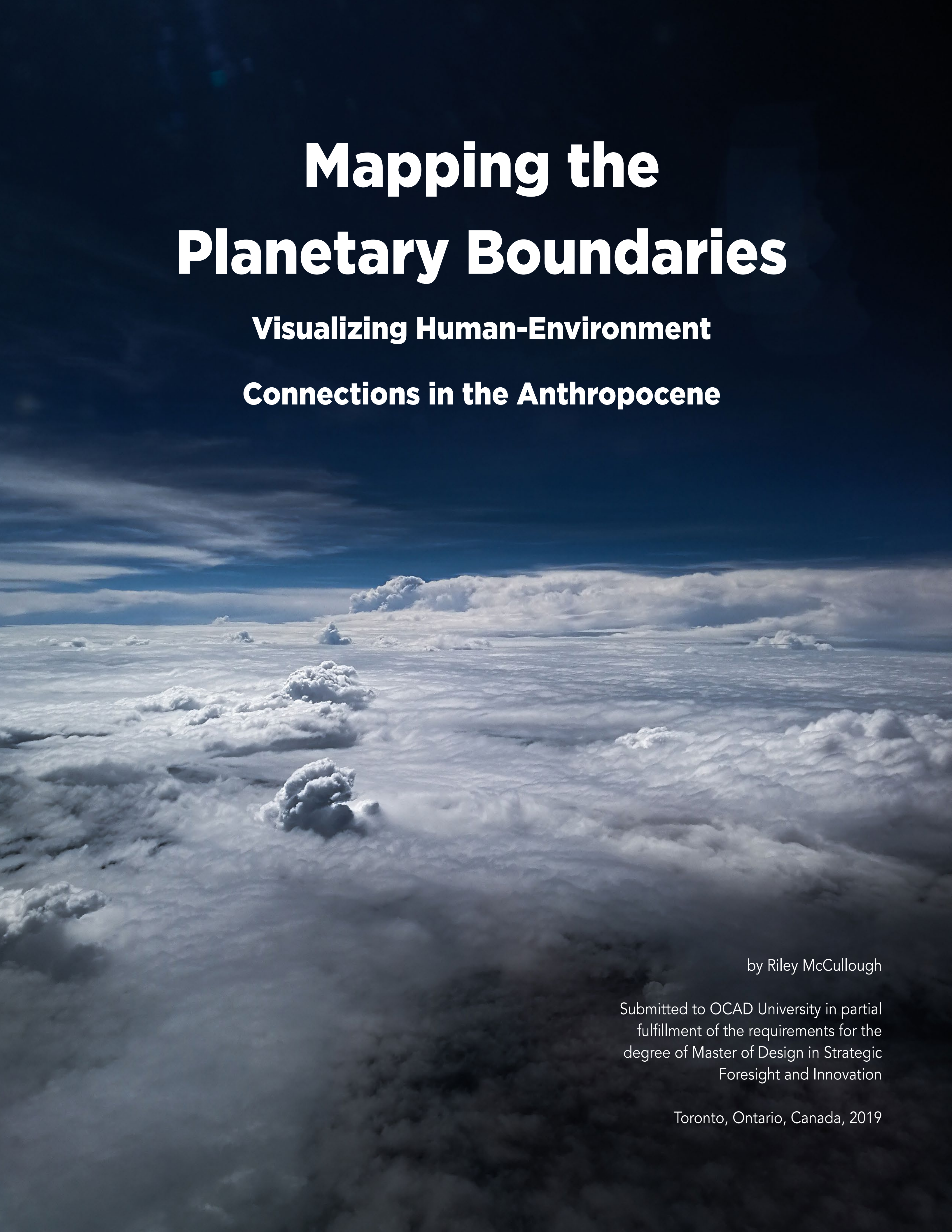

Mapping the Planetary Boundaries

Visualizing Human-Environment Connections in the Anthropocene

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Abstract

The Anthropocene marks the current period in which humanity is living beyond the means of planet Earth and threatening the stability of the climate and other environmental processes that have allowed us to thrive over the past 10,000 years. With increasing anthropogenic stress on the Earth System, the Planetary Boundaries framework aims to determine the thresholds that humanity must operate within to ensure that conditions on Earth remain favourable for human life. This project uses a systems approach to demonstrate the complexity of the Earth System by mapping the relationships between the nine boundaries identified in the Planetary Boundaries framework, as well as the role of anthropogenic actions on those boundaries. This project presents this information in the form of two interactive visualizations that the user can explore to understand the impacts of human activity on the natural environment and the interconnectedness and delicate balance of the Earth System.

Acknowledgments

The completion of this project would not have been possible without the knowledge, guidance, and support of a handful of individuals. To Michele, thank your guidance and feedback throughout this process. To Sam, Sean, Andrew, and Sara, thank you for being a sounding board and providing unwavering emotional support - this wasn't always happy work. To my SFI cohort and professors, thank you for being part of this journey over the past 16 months - you've changed the way I see the world.

This project was undertaken alongside an academic placement with Arup's Foresight, Research + Innovation team in which a portion of my work focused on the Planetary Boundaries as a research topic.

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Executive Summary

According to some scientists, humanity has entered the Anthropocene, the geologic epoch starting in the Industrial Revolution in which humans are the main drivers of change to the functioning of the Earth System.[1] In 2009, Rockstrom et al. developed the Planetary Boundaries framework to understand the extent of human impact on Earth's key systems, and within what boundaries humanity would have to operate for Earth to remain a habitable and safe place for humans.[2]

Although the Planetary Boundaries framework focuses on natural and anthropogenic processes, the systems that underlie the Planetary Boundaries framework - both in the natural environment and in the human dimension - are not highlighted in the current research. Furthermore, information on the planetary boundaries and the anthropogenic actions driving their degradation are not presented in a format that is oriented to those outside the academic communities. While the Planetary Boundaries framework has been used widely within the scientific community, there have been limited opportunities for public engagement. To explore these concepts, this project sets out to answer the research question: How might we represent the relationships between anthropogenic forces and planetary boundaries to better understand the complexity of the Earth System?

Part 1 of the report introduces the topic area and the research process for the project. Part 2 describes the Planetary Boundary framework and outlines its importance in the Anthropocene. Part 3 aggregates detailed information for each boundary, presenting it in a way that demonstrates the cause and effect of human impact and environmental degradation. Part 4 introduces the outputs of this report - two interactive visualizations that demonstrate the complexity of the Earth System. Finally, Part 5 of this report discusses insights that users can gain from the visualizations as well as outlines challenges with the approach taken, offering suggestions for future work.

Introduction

1

Understanding the Earth System

For the past 10,000 years, the Earth has operated in a relatively balanced state with a stable climate and other environmental conditions that have allowed humanity to thrive. This period, known as the Holocene, constitutes a narrow portion of the Earth's history, with 4.5 billion years of natural history leading to these conditions. Since the start of the Industrial Revolution in the 1800s, human activities have been threatening the stable Holocene-like conditions and pushing the Earth into the Anthropocene, the geologic epoch in which human actions are the dominant forces of change on Earth. In recent years, these changes have had increasingly severe impacts on humanity; hurricanes and tropical storms are increasing in intensity, water shortages are becoming more prevalent, and species extinction is on the rise.[3] Many of these impacts are expected to worsen as human development continues to advance, further threatening the ability of the **Earth System** to sustain modern ways of life.[4]

In 2009, a group of scientists and the Stockholm Resilience Institute developed the concept of planetary boundaries, the environmental limits that must not be crossed for Earth to continue to support human life as it has done so throughout the Holocene. The Planetary Boundaries framework provides an understanding of the limited ability of the Earth System to support humanity's advancements and can be used as a starting point to determine which human activities are causing damage that most threatens the environment. Building on the Planetary Boundaries framework, this project uses a systems approach to demonstrate how specific human actions are influencing the natural environment and how environmental changes influence the broader Earth System. The project culminates with two visualizations that demonstrate the complexity of the interactions between and among human activities and Earth system processes.

*The **Earth System** is defined as "the integrated biophysical and socio-economic processes and interactions (cycles) among the atmosphere, hydrosphere, cryosphere, biosphere, geosphere and anthroposphere (human enterprise) in both spatial - from local to global - and temporal scales, which determine the environmental state of the planet within its current position in the universe."*[5]

Purpose and Research Question

In undertaking this research, I wanted to explore the relationship between human actions and environmental degradation, using the Planetary Boundaries framework as a lens. When working with the Planetary Boundaries framework previously, I identified several gaps in the existing research, including a lack of connection between anthropogenic actions and the boundaries, the impacts of degradation in each boundary, and the lack of public discourse surrounding the framework. I also found that the framework, does not explore the interactions between the boundaries.

As a framework intended to communicate the limits of earth's operating system, I wanted to examine how a systems approach to analyzing the planetary boundaries could provide opportunities to understand the complexity and interconnectedness of the human and environmental dimensions of the Earth System. I developed the following exploratory research question to guide this process:

How might we represent the relationships between anthropogenic forces and planetary boundaries to better understand the complexity of the Earth System?

Research Approach

Exploring

The project began with an exploration of the available literature on the planetary boundaries with an attempt to understand its current reach and any existing challenges presented in its structure and dissemination. This review led me to develop the following three challenge areas for the project:

1. **Detailed information on the different boundaries, their drivers, and impacts are not readily available from a single source.**
2. **Information on the Planetary Boundaries framework is not designed for non-specialist audiences.**
3. **The research is not presented in a way that demonstrates the interactions between the nine key systems of the Planetary Boundaries framework.**

Defining

Next, solution areas were defined for each of these challenges. The three solution areas were used to develop the concept for the final output.

Challenge	Solution Area	Solution Concept
Challenge 1	Collect and combine relevant information on the planetary boundaries, their drivers, and their impacts in one comprehensive document.	Create a visual map that allows users to explore the drivers and impacts of anthropogenic change within the Planetary Boundariess framework, ensuring that concepts are presented in a way that can be understood by non-specialist audiences.
Challenge 2	Simplify the concepts and terminology used to describe the Planetary Boundaries framework. Develop a system that allows the reader to explore the boundaries and their details.	
Challenge 3	Use a systems approach to the Planetary Boundaries framework, both at the framework level and at the individual boundary level to map the causality within each boundary and across boundaries.	

Table 1: *Challenges, Solution Areas, and Solution Concept.*

Collecting

Research on each of the boundaries was collected from a variety of sources, including scholarly journals, reports, and publications from international agencies and non-governmental organizations.

Sorting

From the research collected, I used a process based on the ERAF (Entities - Relationships - Attributes - Flows) model[6] to sort the different influential factors into categories based on the DPSIR (Drivers - Pressures - State - Impact - Response) model[7]. For this project, I took a modified approach to the DPSIR model and categorized elements as drivers, pressures, or boundaries, as defined below:

- **Drivers**, or anthropogenic drivers, are the human actions that are causing changes in the Earth System.
- **Pressures**, or environmental pressures, are the environmental conditions resulting from anthropogenic drivers.
- **Boundaries** are the nine planetary boundaries. The name of each boundary was used to demonstrate when conditions would degrade in that boundary.

Visualizing

After sorting the research, I mapped the information to represent the connections and interactions visually. The first visualization maps the interactions between the anthropogenic drivers, environmental pressures and boundaries. The second visualization shows the interactions between the nine planetary boundaries and is intended to be an overview of boundary interactions. Both visualizations were created in the systems-mapping program Kumu and were designed to be interactive.

Limitations

I encountered two main challenges with the design and implementation of the project that resulted in limitations to this work:

1. **The structure of the Planetary Boundaries framework.** The framework is designed to understand the critical limits of Earth's operating system but is not intended to be understood from the perspective of enacting change. Although the framework is an excellent resource for presenting the limits of the Earth System, it raises challenges when attempting to understand the complexity of the Earth System.

2. **The research scope.** This research project was limited to three months and therefore imposed strict limits on the scope of the project. While I initially proposed to incorporate increased levels of detail on Earth System functions and additional socio-economic influences in the Anthropocene, the time frame of this project limited its scope to a high-level assessment of the Planetary Boundaries framework and the causal influences underlying degradation in the Earth System. I have outlined my future intentions for building on this work in the Further Explorations section of this report.

Introducing the Boundaries

2

The Anthropocene

A number of scientists have proposed that the Earth has entered the Anthropocene, the geological epoch in which humans have become the "dominant driver of change in the Earth System"[8] and have fundamentally altered the operating system of the Earth.[9] Changes in the Earth's operations are not new; Earth's state has been continuously changing over the past 4.5 billion years. However, over the past 10,000 - 12,000 years, in a period termed the Holocene, Earth saw a relatively stable climate in which civilization, as we know it today, was able to emerge (Figure 1).

Humans have long relied on the natural environment for survival, often taking advantage of natural resources for processes like developing agriculture and building shelter. For centuries, throughout the Holocene, this was done within the Earth's biogeophysical limits. In the 1800s, the Industrial Revolution triggered the start of a significant increase in environmental degradation caused by human actions; populations have grown dramatically, agriculture and industrial activity have spread, and urbanization has resulted in cities covering more and more land. These activities, among others, marked the start of the Anthropocene and have had dramatic impacts on the biogeophysical systems of the Earth.[10]

In the 20th century, the environmental destruction brought about by the Anthropocene was further fueled by the Great Acceleration - the period after World War II in which the standards of living increased in most areas of the world. During this time, humanity

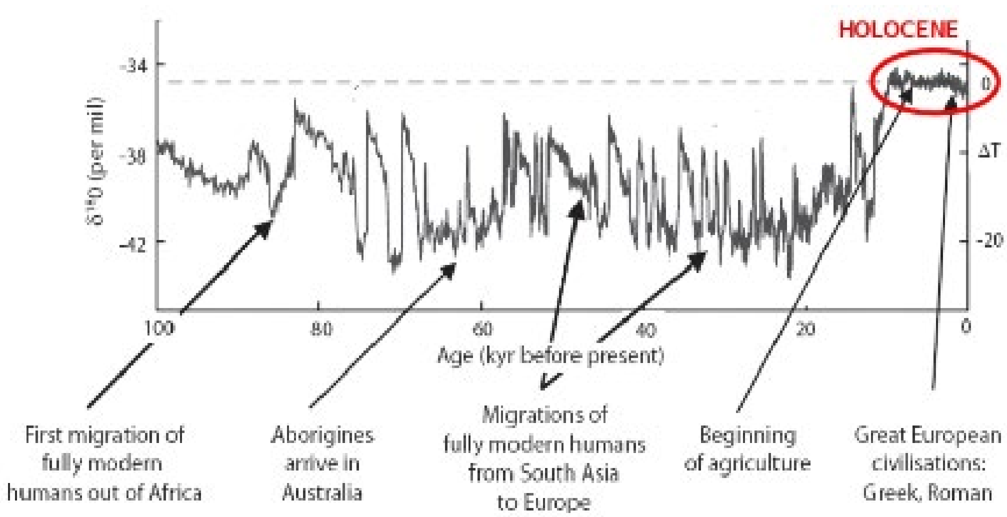
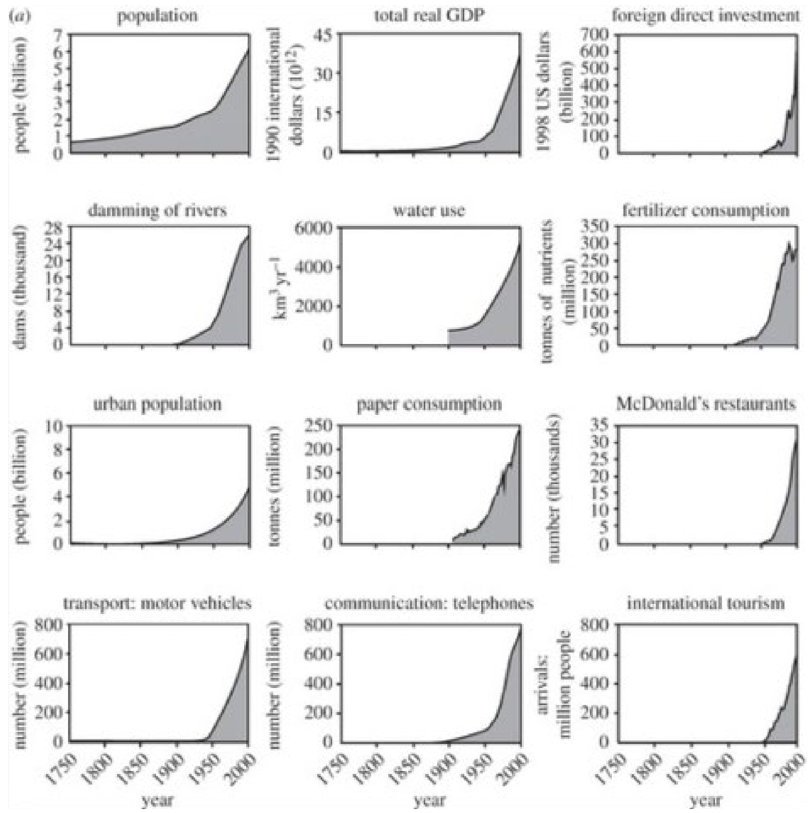


Figure 1. *Temperature variations prior to and during the Holocene.*[14]



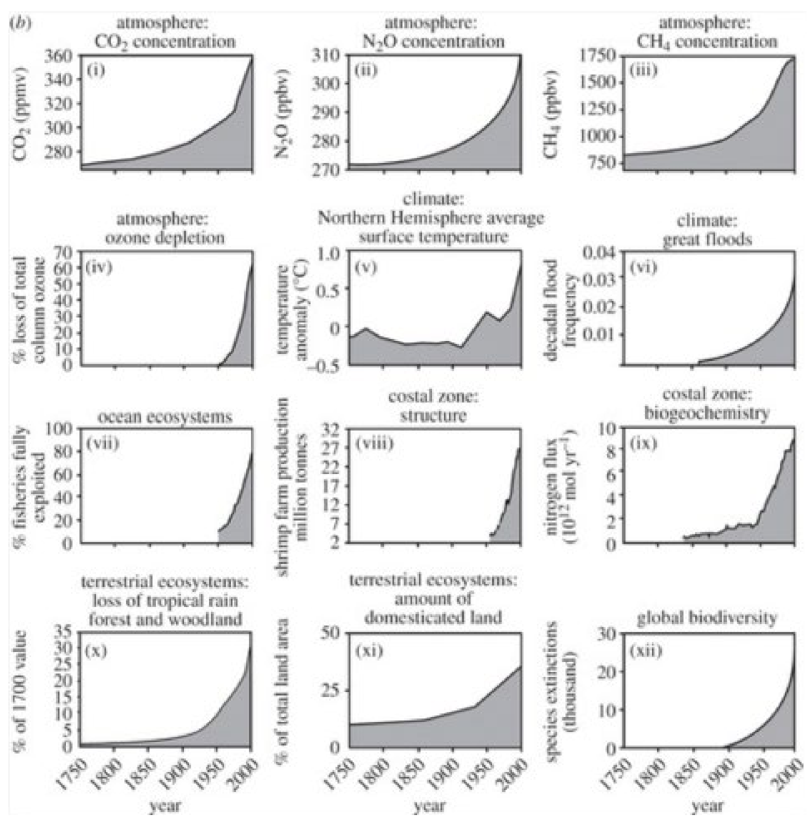


Figure 2a (top). *Societal growth during the Great Acceleration.*[15]

Figure 2b (bottom). *Environmental damage and pressure during the Great Acceleration.*[16]

underwent dramatic changes in population growth, economic growth, and consumption, further degrading the environment and causing changes to the chemical composition of the Earth's atmosphere and oceans on a global level (Figures 2a and 2b). These changes have upset the balance of the Earth System and threaten humanity's ability to rely on Earth processes for elements that are vital to our well-being, such as fresh air and clean water.[11]

Steffan et al. write that human activity may be pushing the planet on a trajectory in which reinforcing feedback loops lead to runaway changes in the Earth System that will be difficult or impossible for humanity to intervene in or stop.[12] The researchers refer to this state as "Hothouse Earth" and note that it would cause increased instability both within the Earth System and societal structures. They argue that this state will be triggered once Earth has reached two degrees of warming (Celsius) compared to preindustrial temperatures. The alternative, according to the authors, is a "Stabilized Earth" in which stewardship of the Earth System avoids runaway feedbacks in our climate and biosphere, resulting in more stable conditions on Earth. The authors write that in order to reach the "Stabilized Earth" position, humans must take "deliberate, integral, and adaptive steps to reduce dangerous impacts on the Earth System."[13]

The Planetary Boundaries

To better understand the limits of the Earth System and humanity's impact on it in the Anthropocene, Rockstrom et al. developed the Planetary Boundaries framework.[17] With the knowledge that human pressure on the Earth System could lead to the destabilization of Earth's biophysical balance, Rockstrom et al. sought to answer the following question: *"What are the non-negotiable planetary preconditions that humanity needs to respect in order to avoid the risk of deleterious or even catastrophic environmental change at continental to global scales?"*[18]

In response, planetary boundaries in nine of the Earth's key systems were proposed. The boundaries are:

Climate Change
Biosphere Integrity
Land-System Change
Biogeochemical Flow
Atmospheric Aerosol Loading
Stratospheric Ozone Depletion
Ocean Acidification
Freshwater Use
Novel Entities

It is important to note that despite using terminology depicting strict thresholds, the Planetary Boundaries framework does not set a threshold based on Earth system tipping points, but instead uses a "zone of uncertainty" with the boundary set at the low end of that zone. Some of the nine key systems in the Planetary Boundaries framework, such as climate change, have well-researched tipping points, or thresholds, which, if crossed, would shift the system into a new, irreversible state. Others, such as land-system change, do not have known thresholds but can shift into a new state caused by repeated degradation. The boundaries for each key system are not set at these tipping points or thresholds, but rather are set conservatively below the thresholds (at the bottom end of the zone of uncertainty) in order to account for unknowns in science and to ensure that the thresholds are not crossed.

Boundaries that are operating within the zone of uncertainty are represented in yellow in Figure 3 and signify a heightened level of risk to the Earth System. Any level of change that occurs below this zone is considered to be within Earth's operating space and the

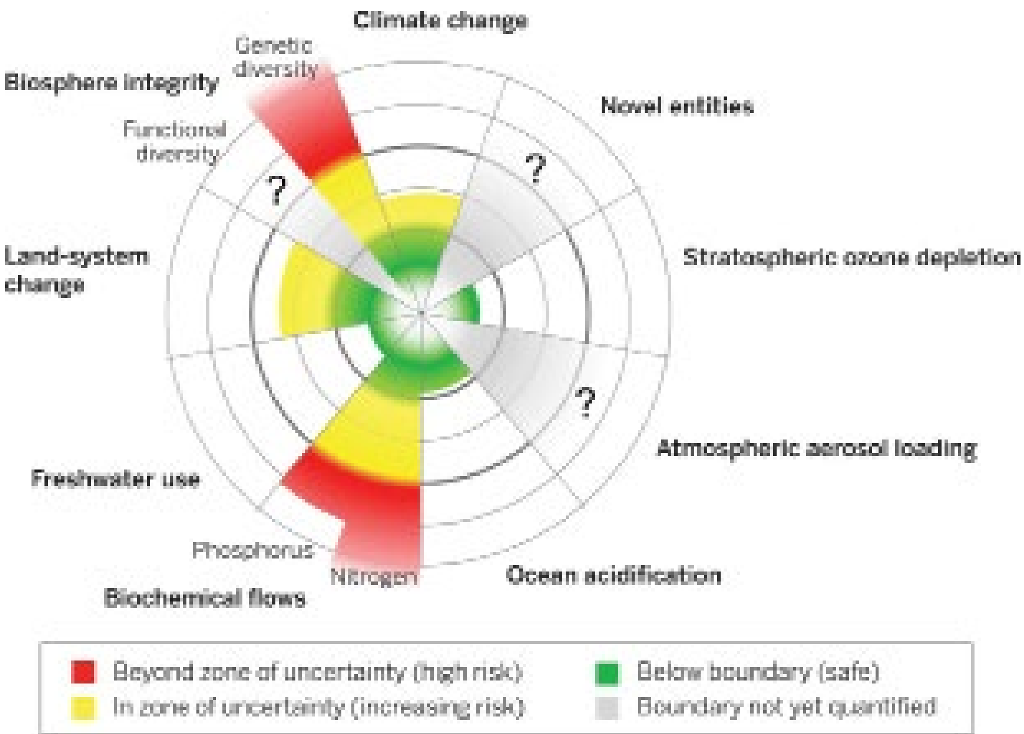


Figure 3. *The Planetary Boundaries and their current status.*[24]

boundary and is represented in green in Figure 3. When changes surpass the boundaries, represented in red in Figure 3, there is a high risk of severe impacts.

In 2015, the framework was updated by Steffan et al. to reflect advancements in scientific knowledge, noting that four of the boundaries (climate change, biosphere integrity, biogeochemical flows, and land-system change) have already transgressed their boundaries or are operating within the zone of uncertainty.[19] Two of the boundaries, novel entities and atmospheric aerosol loading, as well as the functional diversity aspect of biosphere integrity, do not have thresholds set due to limitations in the existing research and measurement capabilities on the subjects. Steffan et al.'s overview of the nine boundaries, their control variables, thresholds, areas of uncertainty, and current status can be found in Appendix A.

The Planetary Boundaries framework has been used widely across the scientific community, sometimes on behalf of governmental decision-makers. Sweden, Switzerland, the Netherlands, and the European Union have used the framework to assess their environmental performance,[20] and other research has used the framework to compare environmental sustainability across nations.[21] Other researchers have also built on the concept of planetary boundaries to create new frameworks that use the boundaries to understand the links between planetary health, societal well-being, and economic growth.[22] Of note is Kate Raworth's Doughnut model, which aims to understand how planetary boundaries and social conditions work with and against each other.[23]

Challenges with the Framework

Several challenges with the Planetary Boundaries framework have been explored in the existing literature.[25] This project focuses on three main themes identified through a review of the literature and my previous work with the framework:

1. **Detailed information on the different boundaries, their drivers, and impacts are not readily available from a single source.**
2. **Information on the Planetary Boundaries framework is not designed for non-specialist audiences.**
3. **The research is not presented in a way that demonstrates the interactions between the nine key systems of the Planetary Boundaries framework.**

Other challenges with the Planetary Boundaries framework that were encountered during this project but not explored in-depth are also described in this section.

Detailed information on the different boundaries, their drivers, and impacts are not readily available from a single source.

The original documents on the Planetary Boundaries framework by Rockstrom et al. and Steffan et al. are limited to high-level information.[26] While they introduce all boundaries, they do not provide detailed information about the drivers or impacts for each. Currently, in order to find in-depth information about each boundary, or to begin to understand the network of drivers and impacts that influences it, one must consult multiple external academic sources.

Aggregating detailed information on all nine boundaries in one document is an essential first step to understanding the complexity that underlies the Planetary Boundaries framework.

Information on the Planetary Boundaries framework is not designed for non-specialist audiences.

The Planetary Boundaries framework is primarily used within academic or scientific communities, and public communication of the framework is limited. While information about the framework has been disseminated through non-academic outlets such as news media, these sources often present high-level information about the boundaries, providing little opportunity for the reader to engage with the framework on a deeper level.[27] When the boundaries are explored in more depth, it is often in the form of an academic journal article or research report intended for the scientific or decision-making communities. In their work on the Planetary Boundaries framework, Meyer and Newman note that the framework is "not easily applied to personal or policy action,"[28] partly due to the complexity of the framework and the operations of the Earth System.

The information presented in the two original reports on the planetary boundaries is intended for scientific audiences or those with specialist knowledge about environmental sciences and Earth systems. Due to the complexity and depth of scientific knowledge available on these subjects, as well as the scientific rigour presented in most scholarly journals, the language and concepts used are often not designed to be easily understood by non-specialist audiences. This challenge exists across the scientific community and is increasing in severity; Plaven-Sigray et al. found a decline in the readability of science journals, with more than one-fifth of scientific abstracts having readability that would be considered as beyond college graduate level English.[29] The use of increasingly complex scientific language is problematic when aiming to demonstrate scientific concepts to non-specialist audiences as "lower readability implies less accessibility, particularly for non-specialists, such as journalists, policy-makers, and the wider public."[30]

Communicating environmental issues like climate change outside of the scientific community is challenging because the causes are mostly invisible, and the impacts lack temporal and geographic immediacy. There is also a disconnect between humans and the natural environment and a lack of adequate signals indicating a requirement for change. Finally, the complexity and uncertainty of the science can discourage potential audiences.[31] Although some researchers argue that climate scientists have done an arguably good job at communicating their research, other areas of environmental concern fail to communicate their information successfully to a broader audience.[32] Grainger et al. highlight the importance of the communication methods of scientific research, arguing that the poor communication of scientific concepts prevents comprehension of the concepts.[33] Engaging audiences on environmental issues is crucial because it can increase awareness and knowledge on a specific issue and influence behaviours, opinions, and policy.[34]

Allowing a broader audience to engage with the Planetary Boundaries framework outside of the scientific and academic communities would allow for increased engagement with the concepts and could be a first step in leading to behaviour changes in individuals.

The research is not presented in a way that demonstrates the interactions between the nine key systems of the Planetary Boundaries framework.

Although Rocktrom et al. note that the nine boundaries are interconnected and that crossing the boundary for one may cause impacts in other boundaries, there is limited research demonstrating the interconnectivity of the different key systems of Earth.[35] Despite existing calls for understanding the Planetary Boundaries framework as a system and incorporating a more significant systemic analysis into the framework,[36] the current research is limited in this area.

Systems thinking can be particularly useful in navigating the complexity of a framework like the planetary boundaries as it allows the researcher or audience member to understand and capture the broader context and analyze the interdependencies with the system or systems. Approaching environmental issues from a systems perspective is essential because systems thinking can help navigate the complexity of the interactions between human systems and the Earth System, as well as understand the implications and consequences of impacts within a system.[37] Lezak and Thibodeau argue that the denial of environmental science, namely climate change, is made possible by "the inherent complexity and scale of the global ecosystem,"[38] and argue for a systems approach to thinking about the natural world. The results of their research found that individuals who understand systems thinking are more likely to apply increased value to the natural environment.[39] These findings are further supported by Davis and Stroink's research that found that "systems thinking posses a stronger ecological worldview and sense of connectivity with nature, harbour biospheric environmental values, and engage in more pro-environmental behaviours than those scoring low on systems thinking."[40]

While some existing research does take a systems approach to the Planetary Boundaries framework,[41] it is limited by either the number of boundaries addressed or the area of concern; most of the research in this area is dedicated to computer modelling and simulations for further research and policy implications. While these Earth System Models (ESMs) are useful in communicating the scale of environmental change to scientists or specialists, they are generally not designed for use by non-specialists.[42] Work by Meyer and Newman on a planetary accounting framework does provide some basic mapping of the interactions between the boundaries, based on the quotas presented in their work.[43] However, this information is not yet available outside of scholarly journals.

Displaying the interactions between the boundaries can lead to an understanding of the complexity of the Earth system as well as an understanding of what areas of action might be most influential or act as leverage points.

Other Challenges

The lack of differentiation of key systems across spatial scales.

The Planetary Boundaries framework generalizes the functioning of Earth's key systems at the global level. However, some of the drivers and impacts noted in the research about the boundaries occur at a local or regional level and are not persistent on a global scale. For example, some drivers and impacts vary in severity and presence in different areas around the world. For example, atmospheric aerosol loading in the form of air pollution occurs mostly at a local or regional scale, and the associated factors cannot be generalized on a global level. For this research, I did not attempt to differentiate local, regional, and global influences in order to manage the project's complexity.

The varying scales of impact across boundaries.

Nykvist et al. and Meyer and Newman[44] attempt to structure the boundaries across the different categories of action in the EEA's DPSIR framework.[45] They note several challenges as some boundaries function as a state of the environment (e.g. the amount of CO2 in the atmosphere), some function as pressures on existing environmental conditions (e.g. the amount of freshwater consumer), and one, biosphere integrity, is categorized as an impact of other boundaries (the rate of extinction).[46] The nonlinear categorization of the boundaries, and the variance in how each boundary acts within the environment presented challenges in the act of mapping the boundaries.

For example, the control variable for the climate change boundary is the atmospheric concentration of carbon dioxide, which is considered an environmental state. This state can have impacts such as increased temperatures. In comparison, in the biosphere integrity boundary, increased temperatures would be seen as a pressure. To address this challenge, a rigid framework like DPSIR was not used to shape the boundary interactions. Instead, I used a modified approach of the DPSIR framework, as described in the Research Approach section of this report, categorizing the different elements as either drivers (human actions), pressures (environmental conditions), or as a boundary itself.

Understanding the Boundaries

The Planetary Boundaries framework highlights nine key Earth systems that are critical to sustaining human life on this planet. Each of these nine boundaries is introduced below and include information on the human activities that drive degradation and the associated impacts of degradation.

3

Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as "a change in climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods."[47] Climate change is recognized as one of the two core boundaries in the framework, meaning it "has the potential on its own to drive the Earth system into a new state should [it] be substantially and persistently transgressed."[48] The control variables for the climate change boundary are atmospheric carbon dioxide concentrations and top-of-atmosphere radiative forcing. The boundary is currently operating within the zone of uncertainty and is expected to degrade further given current trends.[49]

Drivers and Pressures

The emission of greenhouse gases such as carbon dioxide, methane, nitrous oxide, and other well-mixed gases. Carbon dioxide is emitted into the atmosphere through the burning of fossil fuels for electricity, transportation, manufacturing, construction, and the burning of biomass (such as forests). Methane is primarily emitted from agricultural activities, waste management, energy production and biomass burning. Nitrous oxide is a common byproduct of agriculture fertilizer use and fossil fuel combustion. Other well-mixed greenhouse gases are common byproducts of industrial processes, refrigeration and consumer products. The significant contributors to anthropogenic greenhouse gases on a global scale are energy use (primarily for electricity and heating, transportation, and manufacturing and construction), agriculture, industrial processes, waste processing and land-use change and forestry.[50]

Changes that impact how much sun is absorbed or reflected by the Earth. Radiative forcing is defined as the difference between the amount of energy absorbed by Earth and the amount of energy radiated or reflected into space. When more energy is absorbed by the Earth than reflected, the Earth warms.[51] Increases in radiative forcing can be caused by greenhouse gases, ozone and stratospheric water vapour, atmospheric aerosols, and land-use changes. While both greenhouse gases and stratospheric water vapour will increase radiative forcing, atmospheric aerosols and land-use changes have the potential to either increase or decrease radiative forcing dependent on their specific characteristics.[52]

Impacts

An increase in the global temperature and more extreme temperatures. Between 1900 and 2016, the average temperature over the United States increased 1 degree Celsius. Over the past twenty years, the number of high-temperature records far exceeds the number of low temperature records.[53]

Changes in precipitation patterns. For every one degree Celsius of warming, the air can hold approximately 7% more water. As the average global temperature rises, this increases the amount of water vapour in the atmosphere.[54]

Increased rate of extreme weather events, including drought and storms. The disruption of the hydrological cycle reduces the amount of water in some places, which leads to droughts.[55] Warmer oceans are expected to increase hurricane strength and frequency,[56] and increased drought could lead to an increase in fire activity.[57]

Melting of sea ice and other ice stores. In the last 40 years, the annual average Arctic sea ice has decreased between 3.5% and 4.1% per decade. Each year, the sea ice melts for at least an additional 15 days.[58]

Sea level rise. Since 1900, the global mean sea level has risen 16-21 cm, with nearly a third of that happening since 1993. Sea level rise also has downstream impacts, including an increase in coastal flooding.[59]

Increase in ocean temperatures and ocean acidification. Oceans have absorbed an estimated 93% of the excess heat caused by warming since the mid-20th century, increasing more than 0.4 degrees Fahrenheit.[60] They are also absorbing more than 25% of anthropogenic atmospheric CO2, causing an increase in acidity.[61]

Biosphere Integrity

The biosphere refers to all living organisms on Earth, as well as the ecosystem services provided by them. Biosphere integrity refers to the Earth's biodiversity, which impacts the functioning of nearly all aspects of the Earth system.[62] Steffen et al. recognize biosphere integrity as one of the two core systems, meaning it "has the potential on its own to drive the Earth system into a new state should [it] be substantially and persistently transgressed."[63]

In the Planetary Boundaries framework, there are two components of biosphere integrity: genetic diversity and functional diversity. Genetic diversity refers to "the role of genetically unique material as the 'information bank' that ultimately determines the potential for life to coevolve."[64] As data is not yet available to measure genetic diversity, the global extinction rate is used as the interim control variable. Functional diversity aims to measure the role the biosphere plays in the more extensive Earth System. Functional diversity is measured using the Biosphere Intactness Index (BII), which "assesses change in population abundance as a result of human impacts, such as land or resource use…"[65] According to Steffan et al.'s analysis, we have already surpassed the boundary for biosphere integrity.[66]

Drivers and Pressures

The degradation or destruction of local habitats. Habitats are destroyed or degraded through changes in land use, such as deforestation and conversion to land for agricultural purposes, as well as pollution of habitats through novel entities, sewage, or nutrient loading (disruptions in biogeochemical flows). The disruption of water patterns can also change species' habitats. Changes in habitat can impact species' ability to access resources and support themselves, leading to losses in biodiversity.[67]

Climate change. Climate change can impact biosphere integrity through variations in seasonal temperatures and ranges, which in turn can impact reproductive patterns. As climate changes across landscapes, species have also been experienced a shifting in their range towards higher latitudes and elevations. These range shifts could signal natural adaptation among species, but impose impacts on other species within the new ranges and increase the risk of extinction.[68]

Invasive species. Often introduced by humans, invasive species can also threaten local biodiversity by outcompeting native species for resources and habitat.[69]

Agriculture. Agricultural practices impact biodiversity both indirectly, through habitat destruction, and directly; it is estimated that nearly 75% of the world's food now comes from twelve plant and five animal species.[70] This lack of genetic diversity in modern food production not only impacts biosphere integrity but reduces the resilience of our food production systems.[71]

Stratospheric ozone depletion. The increase in UV rays caused by the depletion of the ozone can cause harm to some species and impact biodiversity.[72]

Impacts

Loss of biosphere integrity has impacts across the Earth System as it provides many ecosystem services; the biosphere provides Earth with oxygen, fresh water, fertile soil, raw materials, and food, among others. The biosphere regulates the climate, water, and the flow of nutrients. It also helps filter pollution from the water and air and can act as a sink for carbon dioxide. A loss of biosphere integrity could lead to a disruption in these ecosystem services and cause abrupt changes to the structure and functioning of the Earth system.[73]

Land-System Change

Land-system change refers to "the biogeophysical processes in land systems that directly regulate climate - exchange of energy, water, and momentum between the land surface and the atmosphere."[74] In other words, it refers to the role that land use plays in its connection to the atmosphere.[75] Steffan et al. clarify that the focus of this system is on changes that influence climates beyond a regional scale.[76] The control variable is the amount of remaining forest cover, compared to original forest cover, although the boundary is understood to cover other forms of land conversion and not just deforestation. We are currently within the zone of uncertainty for land-system change.[77]

Drivers and Pressures

Conversion of land for agricultural uses, infrastructure, resource extraction, and urbanization. In the five years following 2010, an estimated 32 million hectares of tropical forest were lost. 73% of this loss was due to large-scale and smallholder farming, while the remainder was due to infrastructure development, resource extraction activities such as mining and logging, and urbanization.[78]

Wildfires and other extreme weather events. Whether set intentionally or occurring through natural causes, fires are also a cause of land-system change, leading to the loss of millions of acres of forest cover every year.[79]

Invasive species. Invasive species can cause damage to natural ecosystems, such as forests. Researchers in Hawaii have found that invasive species can cause damage at a rate that impacts the existing land system on a regional level.[80]

Disruptions in the water cycle. Changes to the water cycle can lead to drought, which impacts trees' survival rates. In forest ecosystems, this can lead to a reinforcing feedback loop in which further tree loss causes increased impacts to the water cycle, resulting in the conversion of forest areas to grassland.[81]

Impacts

The loss and degradation of species' habitats. When land is converted to different uses than its current state, it can degrade, disrupt, or destroy the natural habitat of species, causing them to be displaced.[82]

Changes to radiative forcing. Land-use changes such as deforestation, desertification, and urbanization can all influence Earth's radiative forcing and how much energy is absorbed by the Earth.[83] At the local level, this impact can be seen through an increase in the use of concrete and other dark materials that absorb, rather than reflect the sun's energy, leading urban areas to be as much as 12 degrees Celsius hotter than their rural counterparts.[84]

Increase in atmospheric greenhouse gases. When forests are destroyed, through burning in particular, they release carbon dioxide and other greenhouse gases such as methane and nitrous oxide in the atmosphere, increasing the level of atmospheric greenhouse gases. Additionally, since forests play a key role in carbon sequestration, the destruction of forests reduces the amount of carbon dioxide that is removed from the atmosphere.[85] 15% of all greenhouse gas emissions are estimated to result from the carbon emitted when forests are cut or burned in deforestation and forest degradation.[86]

Disruptions to the water cycle. Trees are a key player in the water cycle as they balance the water between the land and the atmosphere. Destruction of large areas of forest cover can disrupt this balance, causing changes in precipitation and the flow of rivers.[87] Forests can provide up to 70% of their own rainfall through evaporation.[88] Forests play such a substantial role in the regulation of the water cycle that reducing the Amazon rainforest to 40% of its potential tree cover could result in reduced rainfall over 2,000 miles away, while the complete destruction of the Amazon rainforest would impact rainfall in the United States.[89]

Biogeochemical Flows

Biogeochemical flows are the processes that move certain elements, such as nitrogen, phosphorus, carbon, and oxygen, among others, through the living and non-living aspects of the environment. These elements, and their cycling through the environment, are considered critical components of all life, but excess levels of these nutrients can cause environmental damage. The Planetary Boundaries framework only measures nitrogen and phosphorus in the biogeochemical flows boundary. We have surpassed the boundaries for both nitrogren and phosphorus.[90]

Drivers and Pressures

Nitrogen and phosphorus are both naturally occurring elements that are vital to all living organisms. However, since the Industrial Revolution, human sources have been disrupting their natural cycles. Compared to geological sources in pre-industrial times, it is estimated that human activities have moved nine times more nitrogen and 13 times more phosphorus from the Earth's crust and atmosphere into the environment.[91]

Agriculture. Nitrogen and phosphorus fertilizers are heavily used in modern industrial practices, with an estimated half of the human population depending on the fertilizer for their food.[92] Excess fertilizer that is not used by crops can leach into soil and nearby waterways.[93] In the United States, it is estimated that approximately 75-80% of anthropogenic nitrous oxide emissions result from agricultural activities.[94]

Solid waste. Both nitrogen and phosphorous are excreted as waste, and it is estimated that annually, the human population excretes approximately three million tons of phosphorus through urine and feces. As urban populations grow, cities are becoming nutrient hotspots.[95]

Fossil fuel combustion. Fossil fuel combustion emits nitrogen oxides into the atmosphere.[96] In particular, industrial activities and energy production contribute significantly in this area, with an estimated 20% of anthropogenic nitrous oxide emissions in the United States come from the industrial sector and the energy production sector.[97]

Impacts

Climate change. In its atmospheric form, nitrogen is considered to be a potent greenhouse gas. Nitrous oxide, a gaseous form of nitrogen that is mostly emitted from fertilized soil, animal waste and combustion of fossil fuels and biomass, is considered to be 300 times more effective at heating the atmosphere than carbon dioxide.[98]

Atmospheric pollution. Fossil fuel combustion releases nitric oxide into the atmosphere, which can combine with other elements to form smog and acid rain.[99] Atmospheric nitrogen can also encourage secondary particulate matter in the atmosphere.[100] Excess amounts of nutrients, like nitrogen and phosphorous, in waterways is also considered a form of pollution.[101]

Aquatic acidification and eutrophication. When an excess amount of nutrients, such as nitrogen and phosphorous, are deposited into waterways, eutrophication can occur and an increase in algae growth, which is often considered to be toxic. When these algae die, they consume oxygen and release carbon dioxide into the water. The lack of oxygen can cause die-offs in local aquatic species, and the increase in carbon dioxide can cause the water to acidify.[102] Nitrogen in waterways can lead to low or no oxygen conditions, killing off local species and contributing to eutrophication and toxic algal blooms.[103]

Biosphere integrity. Researchers have identified the deposition of atmospheric nitrogen as a threat to plant diversity as nitrogen can cause species compositions to change over time, often resulting in a decline in biodiversity and the changing in the composition of species habitats.[104] As many species rely on nitrogen as a major nutrient, changes in the amount of available nitrogen can "influence the productivity of ecosystems and change the competition between species and biological diversity."[105]

Stratospheric ozone depletion. Nitrous oxide, a greenhouse gas that can come from agricultural practices and the burning of fossil fuels, is the most dominant ozone-depleting substance in the 21st century.[106]

Atmospheric Aerosol Loading

Aerosols are small particles suspended in the atmosphere that can either absorb or reflect the sun's light, leading to changes in the Earth's energy balance and interacting with water vapour to impact cloud formation. Atmospheric aerosols vary in size and chemical composition, with different forms of aerosols having different environmental impacts; some contribute to global warming while others contribute to cooling. To the human eye, atmospheric aerosol loading is most recognizable as haze or smog. The atmospheric aerosol level is included as a planetary boundary due to its ability to impact the climate system and its adverse impacts on human health such as cancer and respiratory disease.[107] A boundary for atmospheric aerosol loading has not yet been determined.[108]

Drivers and Pressures

Atmospheric aerosols have both natural sources and anthropogenic sources.[109] Ocean spray, mineral dust, and forest fires are some of the leading natural sources of atmospheric aerosols and comprise the majority of atmospheric aerosols. Anthropogenic sources of atmospheric aerosols are only come from natural sources about 20% of the time.[110] However, they are increasing, and their impacts on the climate system are not well known.

Industrial dust. The primary industrial sources of atmospheric aerosols are from vehicles and road dust, the combustion of fuel and coal, the manufacturing of cement, metallurgy, the incineration of industrial waste, and dust from agricultural land and other land-based practices (such as mining and resource extraction). Over the last 20 years, these sources have had the most visible impacts on environmental quality.[111]

Fossil fuel combustion. Coal power plants and vehicular emissions contribute significantly to the level of atmospheric aerosols. These emissions are expected to double between 2016 and 2040 as fossil fuel reliance increases, particularly in countries like China and India. Soot particles from fossil fuel combustion, which are dark in colour, absorb energy from the sun, increasing the global temperature when there are large amounts.[112]

Waste and biomass burning. Atmospheric particles resulting from biomass burning, including from agricultural burning and uncontrolled fires, can have global and regional climate impacts. The intentional burning of biomass for land clearing and agricultural purposes contributes significantly to atmospheric aerosol loading.[113]

Agriculture. Humans emit large amounts of nitrate aerosols into the environment in the form of ammonia and nitric oxide, and agricultural use of fertilizer is a significant contributor of ammonia.[114] The burning of crop residue and certain tillage practices also contribute to the release of particulate matter and atmospheric aerosol loading.[115]

Impacts

Pollution. Atmospheric aerosol loading impacts air pollution most directly through the emission of particulate matter. The human health impacts of large amounts and concentrations of atmospheric aerosols are well-known; in the mid-2000s, fine particulate matter was estimated to have caused nearly 6.4 million deaths per year.[116]

Disruption of the water cycle. Aerosols can interfere with water vapour in the atmosphere and lead to changes in cloud formation and the distribution of water. Although not yet measured on a global scale, this impact has been demonstrated through research on Asian monsoon patterns.[117]

Desertification. Atmospheric aerosols in the form of dust can contribute to desertification. As dust particles absorb sunlight, they warm the air around them, inhibiting storm cloud formation. Without storm clouds, areas experience less rainfall and can contribute to desert expansion.[118]

Changes in radiative forcing. Depending on their composition and size, atmospheric aerosols can absorb or reflect sunlight. When aerosols absorb the sun's energy, it can cause atmospheric heating, while aerosols that reflect the sun's energy can cause atmospheric cooling.[119] The cooling effects of atmospheric aerosols are estimated to have masked the warming effects of continental warming due to greenhouse gases by about 33% over the past fifty years.[120]

Stratospheric Ozone Depletion

The stratospheric ozone layer is a part of the atmosphere that lies about 15 to 30 kilometres above the Earth's surface and filters ultraviolet (UV) radiation from the sun. Depletion of stratospheric ozone results in an increase in the amount of UV radiation reaching the Earth's surface, which can result in negative impacts on human health and other species.[121] In the 1980s, it was discovered that there was a stratospheric ozone hole over portions of Antarctica at certain times in the year, signalling a crossing of this boundary.[122] This discovery led governments to pass the Montreal Protocol, a global agreement passed in 1987, which saw the phasing out of many ozone-depleting chemicals. The Montreal Protocol has proven to be a successful example of global action; most ozone-depleting substances (ODSs) are no longer produced and humanity is now expected to remain within the boundary.[123]

Drivers and Pressures

Ozone-depleting substances. The stratospheric ozone layer is threatened by chemical compounds that are referred to as ODSs. Chemical compounds containing chlorine or bromine, such as chlorofluorocarbons (CFCs, hydrochlorofluorocarbons (HCFCs), methyl compounds, and halons, are considered ODSs. When ODSs enter the stratospheric level of the atmosphere, they are broken down by the sun's UV rays into chemicals that degrade the ozone layer. Although most uses of these chemicals have been phased out by the Montreal Protocol, they were widely used in aerosol sprays, refrigerants, air conditioners, fire extinguishers, solvents, and as blowing agents for foams (such as insulation) and packing materials, as well as other household and industrial products.[124]

Nitrous oxide. Research in 2009 found that since the phasing out of the ODSs covered by the Montreal Protocol, nitrous oxide has been the dominant ozone-depleting substance.[125] Nitrous oxide is a greenhouse gas with natural sources such as soil and human-made sources, including agricultural processes (particularly nitrogen fertilizer use and soil cultivation), animal waste, the burning of biomass and fossil fuels, and other industrial processes.[126]

Impacts

Damage to the ozone layer in the stratosphere can lead to the development of an ozone hole which allows higher levels of UV to reach Earth's surface, causing a variety of impacts:

Human health and animal impacts. Increased exposure to UV rays can cause cancer and cataracts and can negatively impact the immune system, leading to an increase in infectious disease.[127]

Damage to plant productivity. Research has shown that pants that are exposed to increased UV levels see reductions in their leaf size, which limits their ability to perform photosynthesis, a process essential to plant growth. Exposure to UV rays can also negatively impact the reproduction rates of plants and influence how they use different nutrients.[128]

Impacts on aquatic life. Research suggests that increased UV levels can impact the productivity of marine ecosystems. Increased UV levels can impact the distribution of phytoplankton, which forms the base of aquatic food webs. UV rays can also impact the development of certain aquatic species, such as shrimp, crabs, and amphibians, potentially impacting their reproductive abilities.[129]

Ocean Acidification

Oceans are one of the Earth's main sinks for carbon, having absorbed nearly 30% of anthropogenic carbon dioxide from the atmosphere between 1994 and 2007.[130] When the ocean absorbs carbon dioxide, carbonic acid is formed, which makes the ocean more acidic. As the ocean's chemical composition changes, it makes it more difficult for some marine species to develop their shells and skeletons. Rockstrom et al. set the boundary for ocean acidification at a level that allows aquatic organisms such as corals, shellfish, and plankton to survive.[131] As ocean acidification is directly related to levels of carbon dioxide, the boundary for ocean acidification is closely linked to that of climate change. Although we have not yet crossed the boundary, research shows that ocean acidity has increased 30% compared to pre-industrial times, and the current rate of acidification is "at least 100 times faster than at any other time in the last 20 million years."[132]

Drivers and Pressures

Atmospheric carbon dioxide. Carbon dioxide is emitted into the atmosphere through the burning of fossil fuels for electricity, transportation, manufacturing, construction, and the burning of biomass (such as forests) and is absorbed by oceans.[133]

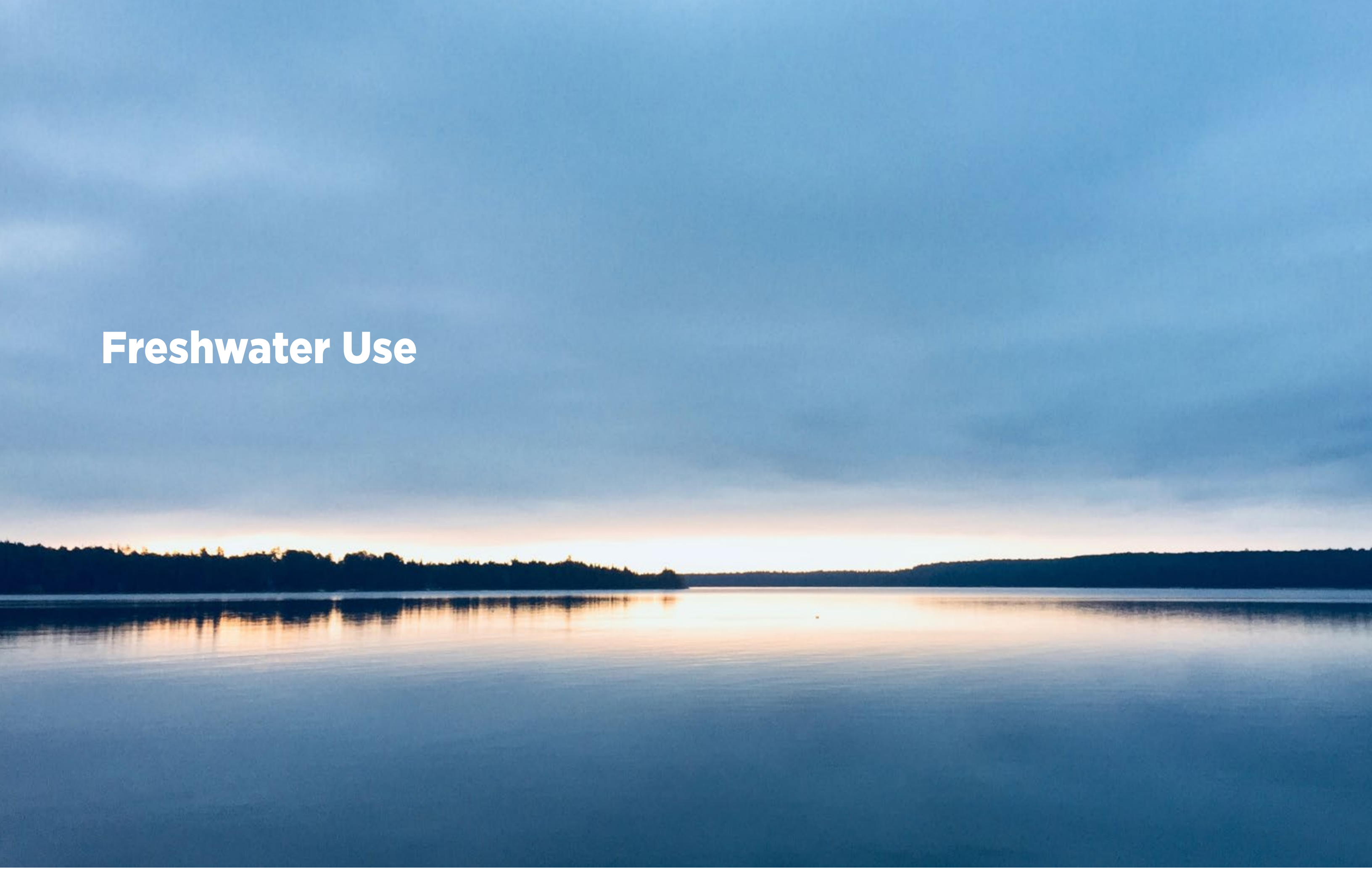
Nutrient runoff. Nutrients such as nitrogen and organic carbon, primarily used in fertilizer in agriculture, can be deposited into coastal areas through runoff. An excess of nutrients can cause eutrophication, in which algae growth increases. When these algae die, they consume oxygen and release carbon dioxide into the coastal waters, increasing acidification in coastal areas.[134]

Impacts

Impacts on aquatic animals. When the ocean absorbs carbon dioxide, it triggers a series of chemical reactions, which result in a reduced amount of carbonate ions and calcium carbonate, which are essential for building shells and skeletons of many marine animals. A decrease in the amount of carbonate ions and calcium carbonate makes building and maintaining shells difficult or impossible, and can have severe impacts on organisms such as oysters, clams, corals, sea urchins, and certain plankton. Increased ocean acidification can also impact the physiological development of marine organisms.[135]

Altering of the aquatic food chain. Increased acidity impacts some species that form the foundation of food chains in the oceans. If these species are impacted severely, it could lead to the destabilization of entire aquatic ecosystems.[136]

Freshwater Use



Globally, it is estimated that nearly four billion people experience water scarcity in at least one month of the year.[137] Pressure from human activities is already the dominant force driving changes to global freshwater systems. With water shortages expected in the future, these impacts will only become more severe. Humans alter water systems through damning and agricultural practices, and the global water cycle is heavily impacted through land-system changes. It is estimated that 35% of the world's rivers run dry before reaching the oceans that have long been their destinations due to human consumption along the river basins.[138] In 2018, nearly 70 countries experienced water stress.[139] Stress on freshwater systems is mostly local - while some areas have far surpassed a safe consumption of freshwater, others are operating safely within the boundary.

Drivers and Pressures

Freshwater consumption in agriculture, industry, and energy production. Globally, 10 million tons of freshwater is used by humans every day. About 70% of this water is used for agriculture, 15% is used for energy production, 10% is used for domestic purposes, and 5% is used in manufacturing and industry processes.[140]

Land-system changes. Certain land uses, such as forests, play a vital role in the water cycle as they absorb water from the land and move it to the atmosphere through a process called transpiration. As mentioned earlier, the removal of forest cover can severely disrupt this balance, putting pressure on the global water system.[141]

Polluted water sources. There are many causes of water pollution, and pollution can enter waterways directly or indirectly through runoff or melting snow. Nonpoint source pollution, which is not deposited directly into waterways from the source, is a significant issue. Many pollutants, including agricultural products, oil and chemicals from industry and transportation, bacteria, and pet waste, among others, enter waterways through this process. Polluted freshwater is often unsafe for consumption as it can cause human health issues. When polluted sources of freshwater are unusable, the strains on other freshwater systems is increased.[142]

Flow modification. Social infrastructure such as reservoirs, dams, canals, and aqueducts are used for energy production or to ensure water security for populations. These interventions have transformative impacts on freshwater systems, including the fragmentation of the original water source, increased rates of evaporation, and impacts on aquatic species.[143]

Climate change. Climate change puts pressure on existing freshwater sources through increased temperatures and changes in precipitation patterns that are used to recharge freshwater stores.[144] For example, an increase in temperature can reduce the amount of snowfall in some mountainous regions, causing watersheds that typically rely on these snow melts as a source of water in the spring to have reduced flows.

Impacts

Biosphere integrity. Although freshwater only covers about 0.8% of the Earth's surface, freshwater systems support at least 100,000 species, 6% of species known on Earth.[145] Research of 4,000 cities, with as many as 1.7 billion residents, found that 85% of the sources that supply water to these regions have high biodiversity value.[146] When freshwater sources are overused, polluted or modified, they contribute to the destruction and degradation of habitats for these species, limiting their ability to survive.

Food security. Agriculture is responsible for nearly 70% of the world's freshwater consumption, and water is critical to the support of agricultural systems. As the population is expected to grow in the coming decades, stress on water sources could lead to food scarcity issues.[147]

Novel Entities

Novel entities are a critical component of modern life; they are present in nearly every single economic sector and most aspects of daily life. Novel entities are defined as "new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects."[148] Novel entities are difficult to quantify as they cover chemical pollution across a wide range of sources including, heavy metals, radioactive compounds, genetically modified organisms, and other human-made organic compounds.[149] Despite novel entities not having an identified boundary, Rockstrom et al. justified their inclusion of novel entities in the framework because their human and environmental impacts were evident on a global scale.[150]

Drivers and Pressures

Industrial and manufacturing activity. Almost all industrial and manufacturing processes include novel entities in some form. It is estimated that there are over 100 million human-made chemicals used in industrial processes. Mining and ore processing, metallurgy, pharmaceutical manufacturing, leather tanning, gold-mining, product and chemical manufacturing and the dye industry are examples of some of the leading sources of novel entities in this area.[151]

Agriculture. Many fertilizers and pesticides are considered to be novel entities.[152] Genetically modified organisms, which alters the genetic makeup of crops, usually for increased crop output or nutrient presence, are also considered novel entities.[153]

Consumer products. Many consumer products on the market today contain novel entities, including most household cleaning products, personal care and cosmetic products, furniture, and clothing. Plastic, a staple of many aspects of everyday life, is considered a novel entity.[154]

Impacts

Climate change. Some novel entities are considered greenhouse gases and can contribute to climate change, while others are created from materials like petroleum, which releases carbon dioxide when they degrade or if they are burned as waste.[155]

Pollution. Novel entities can cause pollution in the atmosphere, soil and water sources. In water, this pollution can occur either through the discharge of novel entities directly into the water source or after being deposited into water sources from the atmosphere. Pollution of the atmosphere can lead to human health impacts, and pollution of water sources can have severe impacts on aquatic ecosystems. Soil pollution from novel entities can be caused by the dumping of waste, chemical spills, mining activities, or pesticides, among other sources.[156]

Biodiversity. Novel entities can impact biodiversity both through directly impacting the health of animals and other organisms, as well as through the pollution of their habitats, as previously mentioned.[157] Plastic, which is considered a novel entity, is of particular concern due to its ability to be consumed by animals. The IPBES estimates that at least 267 species, including 86% of marine turtles, 44% of seabirds, and 43% of marine mammals are impacted by plastic.[158]

Mapping the Boundaries

Using the information gathered in the "Understanding the Boundaries" section of this report, two visualizations were created to demonstrate the complexity of the Earth System and the influences and interactions between and among its human and environment dimensions.

The first visualization is called **Boundary Influences**, and maps at the greater network of drivers and pressures among all boundaries.

The second visualization is called **Boundary Interactions** and maps only the connections between the nine planetary boundaries.

These visualizations and the information stored within them are presented in this section.

4

Boundary Influences

The first visualization explores the influences between human actions and the environment. To create this visualization, the information for each boundary provided in the previous section of this report was aggregated and sorted to uncover the human actions, environmental pressures, and impacts that played the most significant role across all the boundaries. This sorting exercise resulted in eleven anthropogenic drivers and eleven environmental pressures, which are listed below, along with their descriptions.

Anthropogenic Drivers

Agriculture

Agriculture includes all activities related to the agricultural industry, including fertilizer use, land tilling, soil degradation, crops and livestock, land clearing, and land management.

Industry and Manufacturing

Industry and manufacturing include all processes used in the fabrication and processing of products, including the conversion of raw materials to products. It includes the creation of chemicals, textiles, machinery, and materials, such as metals or plastics.

Energy Production

Energy production refers to the creation of energy from both renewable and nonrenewable sources. Although they overlap, this category is differentiated from the fossil fuel combustion category as not all forms of energy production, such as hydropower or solar power, stem from fossil fuel combustion.

Fossil Fuel Combustion	Fossil fuel combustion refers to the burning of fossil fuels, typically for energy purposes. Fossil fuel combustion includes the burning coal, oil and natural gas, and contributes to the emission of greenhouse gases and other air pollutants.
Resource Extraction	Resource extraction refers to the process of extracting materials from the natural environment. Logging and mineral mining are examples of resource extraction.
Solid Waste	Solid waste refers to all forms of waste, including sewage and material waste that is typically sent to a landfill.
Transportation	Transportation includes all forms of travel, including cars, planes and boats.
Fires	Fires can occur from both anthropogenic and natural sources and are increasing in intensity and occurrence with increased temperatures and drought. Fires can be considered both an anthropogenic impact (human actions are often causes of fires, and some fires are intentionally set, as in the case of land clearing) and environmental pressures and impacts (lightning storms can cause the start of wildfires or bushfires in areas experiencing drought conditions). They are included as an anthropogenic driver as intentionally set fires cause severe environmental degradation on a global scale each year.
Urbanization	Urbanization refers to the development of human settlements and cities.
Ozone-Depleting Substances (ODSs)	Ozone-depleting substances (ODSs) are chemical compounds containing chlorine or bromine, such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl compounds, and halons. These chemical compounds were mostly phased out with the Montreal Protocol. They were commonly found in aerosol sprays,

	refrigerants, air conditioners, fire extinguishers, solvents, and as blowing agents for foams (such as insulation) and packing materials, as well as other household and industrial products.[159]
Invasive Species	Invasive species are species that are not native to a location. Invasive species can be introduced through human activities or environmental changes and often cause damage to the local environment.[160]

Environmental Pressures

Degraded Water Sources	Degraded water sources refer to a decrease in water quality, typically caused by pollution and runoff.
Disruption of the Water Cycle	The water cycle is the process of how water evaporates from Earth's surface into the atmosphere, cools and condenses into rainfall or snow in clouds, and falls to the Earth's surface as precipitation. Trees and other plants play a vital role in the regulation of the water cycle through the process of uptaking water from the ground and releasing it to the atmosphere through their leaves in a process called evapotranspiration. Actions such as deforestation disrupt this process.
Eutrophication	Eutrophication is the process of excess plant and algae growth, typically caused by the increased availability of nutrients (such as nitrogen and phosphorous) or carbon dioxide. Although eutrophication can occur naturally, anthropogenic activities have caused an increase in the rate, extent, and occurrence of eutrophication in bodies of water. Eutrophication and the associated algal blooms have several consequences, including degraded water quality. Furthermore, when the algae die, they consume oxygen and result in a "dead-zone" in which there is not enough oxygen for other aquatic species to survive.[161]

Extreme Weather

Extreme weather events include heat waves, droughts, heavy rains, floods, hurricanes, and other storms such as winter storms and tornadoes. Although these have occurred throughout time, there is strong evidence to suggest that they are growing in occurrence and intensity with climate change. Heatwaves are abnormally hot weather conditions that last for days or weeks. Droughts occur when higher temperatures increase the rate of evaporation from plants, resulting in drying conditions on land. In the United States, increased rainfall and more torrential downpours have occurred steadily since the early 1990s, and have led to disastrous floods. Floods include flash floods, urban flooding, coastal flooding, and river flooding. Hurricanes have also increased in intensity and occurrence with the rise of climate change due to different atmospheric conditions and an increase in sea surface temperatures. Although there is some scientific evidence to suggest a changing climate may be causing more and worse winter storms and tornadoes, the exact impacts are uncertain, and they continue to be studied.[162]

Greenhouse Gases

Greenhouse gases are gases in the atmosphere that trap energy (heat) from the sun, causing a heating effect in the atmosphere, similar to the functioning of a greenhouse. The Kyoto Protocol describes carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride as the leading greenhouse gases, but notes that carbon dioxide, methane and nitrous oxide are crucial as they are primarily caused by human activities.[163] The significant contributors to anthropogenic greenhouse gases on a global scale are energy use (primarily for electricity and heating, transportation, and manufacturing and construction), agriculture, industrial processes, waste processing and land-use change and forestry.[164]

Habitat Loss, Fragmentation, and Degredation

Habitat loss, fragmentation, and degradation are significant impacts of land-system change and central pressure on biodiversity loss. Habitat loss refers to the absolute destruction of a species' habitat. Habitat fragmentation means the loss of portions of a species' habitat and may restrict movement or migration of the species.

Habitat degradation refers to the weakening of a species' habitat, often through partial destruction or pollution.

Increase in UV Rays

When the sun emits energy, it emits various ranges of energy with different wavelengths. About 2% of this energy is considered high-energy ultraviolet (UV) radiation. The amount of UV radiation that hits Earth is dependent on the location of the sun, the amount of ozone in the atmosphere, the cloud cover, and pollution. UV-B, a particular type of UV radiation, causes health impacts to plants and animals, including cancer, sunburns, and eye damage.[165]

Melting of Ice Stores

Melting of ice stores is included as an environmental pressure due to its important impacts on sea-level rise and role in the feedback loop between greenhouse gases and a warming climate.

Pollution

Pollution refers to the introduction of harmful materials into the environment. Water pollution, air pollution, and soil pollution are the main types of pollution included in this category.

Radiative Forcing

Radiative forcing is defined as the difference between the amount of energy absorbed by Earth and the amount of energy radiated or reflected into space. When more energy is absorbed by the Earth than reflected, the Earth warms. Conversely, when the Earth reflects more energy than it absorbs, the Earth cools. Increases in radiative forcing can be caused by greenhouse gases, ozone and stratospheric water vapour, atmospheric aerosols, and land-use changes.[166]

Sea Level Rise

Since 1900, the global mean sea level has risen 16-21 cm, with nearly a third of that happening since 1993. Warming of the earth's temperature is the primary driver of sea-level rise, as it causes oceans to expand as they absorb heat, causes the loss of ice sheets through melting, and it causes the loss of glaciers in a similar manner.[167]

Boundary Influences Visualization

This information was used to create a visualization of the relationships between anthropogenic actions and the boundary framework (Figure 4) in Kumu, a systems-mapping platform. Additional details about the display of this visualization can be found in the Discussion section of this report.

An interactive version of this visualization, made using the systems-mapping program Kumu, can be viewed at http://bit.ly/38gD6Nk. Instructions on how to navigate this visualization in Kumu can be found in Appendix B - Visualization Links and Instructions.

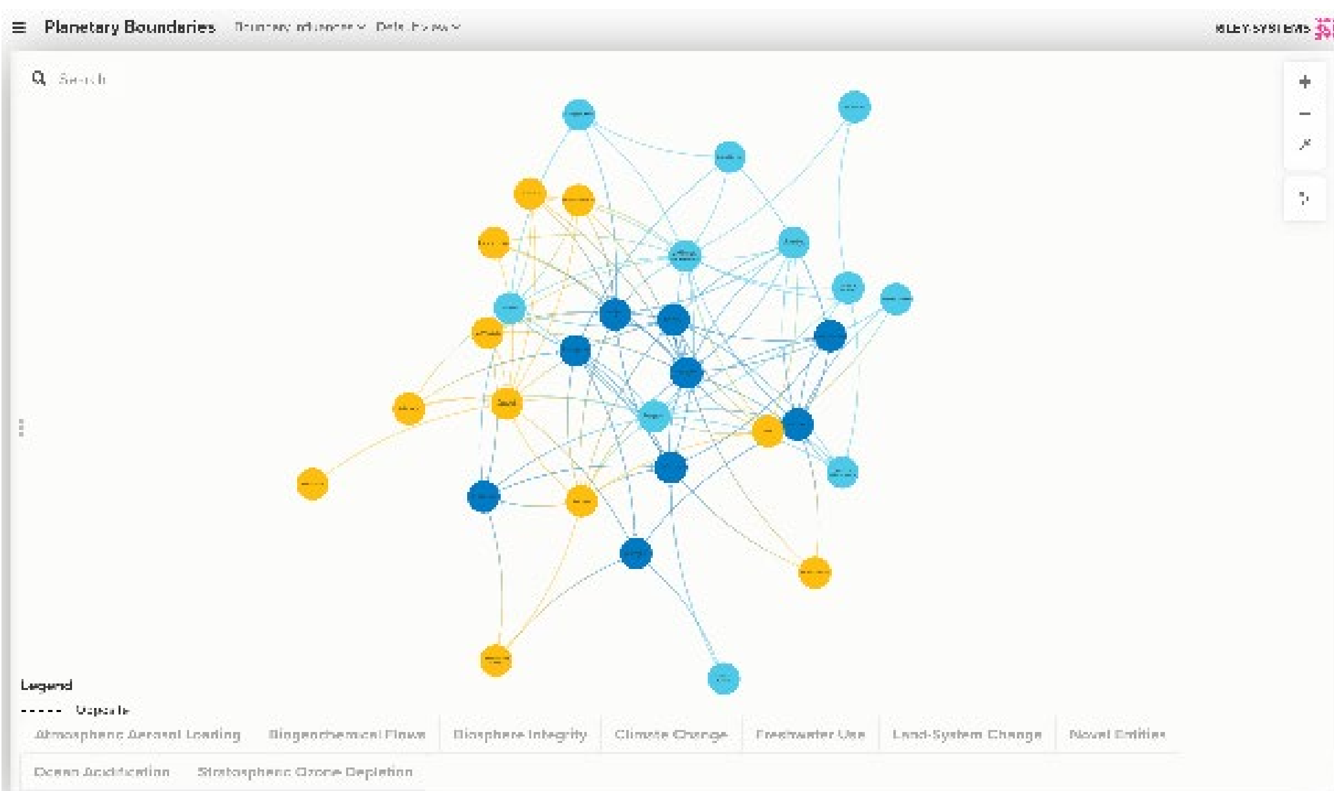


Figure 4. *Still image of the boundary influences visualization.*

Boundary Interactions

In researching the drivers and impacts of the boundaries, it became clear that there were strong links between various boundaries. Visualizing the boundary interactions is useful to understand the interconnectedness of the Earth System and highlights how degradation in one boundary can lead to impacts across the entire Earth System. To demonstrate these interactions, I summarized the information presented previously on the influences across boundaries in order to map boundary-to-boundary interactions. Table 1 highlights these influences, and descriptions of each of these interactions is included below.

1. **Climate change impacts biosphere integrity.** As the climate changes, species must adapt to new seasonal temperatures and temperature ranges, which can impact their reproductive patterns and cause them to migrate to high latitudes, out of their natural habitat.

2. **Climate change and land-system change impact each other.** Changes in temperatures, participation patterns and weather events can force land-system changes. When forests are removed, they can no longer absorb carbon dioxide from the atmosphere, furthering climate change. Also, changes in land use can impact the Earth's radiative forcing, causing climate changes.

	CC	BI	LSC	BGF	AAL	SOD	OA	FWU	NE
CC		1	2			5	6	8	
BI			9	10				14	
LSC	2	9		16	17			18	19
BGF	3	10	16				20	21	
AAL	4	11	17					24	
SOD	5	12							
OA	6	13			23				
FWU		14	18	21					
NE	8	5	19	22	25	26		27	

Legend

CC = Climate Change
BI = Biosphere Integrity
LSC = Land-System Change
BGF= Biogeochemical Flows
AAL = Atmospheric Aerosol Loading
SOD = Stratospheric Ozone Depletion
OA = Ocean Acidification
FWU = Freshwater Use
NE = Novel Entities

***Table 2.** Boundary Interactions.*
How to read this table: In this table, the direction of influence moves from the column on the left to the row at the top. Influences that are one-directional (only moving from the boundary indicated in the column on the left to the boundary indicated in the row on the top) are highlighted in light grey, while bidirectional influences are highlighted in dark grey. For example, the cell labelled "1" demonstrates that Climate Change influences Bisophere Integrity, while the cell labelled "2" demonstrates that Climate Change and Land-System Change influence each other. The numbers in each cell are associated with the descriptions provided in this section.

**The above table has been developed based on a model created during an academic placement with Arup's Foresight, Research + Innovation team.*

3.	**Biogeochemical flows impact climate change.**	Nitrogen-based fertilizers can convert to nitrous oxide, which is a greenhouse gas that is 300 times more effective at heating the atmosphere than carbon dioxide.
4.	**Atmospheric aerosol loading impacts climate change.**	Atmospheric aerosols impact the Earth's energy absorption, causing changes in the Earth's radiative forcing. While some aerosols can increase Earth's temperature, aerosols are primarily thought to have cooling impacts on the Earth's climate due to their ability to reflect sunlight.
5.	**Climate change and stratospheric ozone depletion impact each other.**	Ozone depletion is not a significant factor in climate change, but the two are connected. Ozone traps heat from the sun in two layers of the Earth's atmosphere, leading to warming; ozone holes have had cooling effects. Nitrous oxide contributes to both climate warming and stratospheric ozone depletion, as do most ODSs.
6.	**Climate change and ocean acidification impact each other.**	Carbon dioxide is a primary driver for both worsening climate change and ocean acidification. Oceans absorb a large portion of carbon dioxide (and heat) that would otherwise have stayed in the atmosphere; since 1995, oceans have stored 93% of the heat trapped by greenhouse gas emissions. Increased ocean acidification can lead to the increased production of a sulphur compound that, when emitted to the atmosphere, contributes to the warming of Earth by reducing the amount of solar radiation that is reflected).
7.	**Climate change impacts freshwater use.**	Climate change has significant impacts on precipitation patterns, decreasing the stability and security of existing and historically reliable water sources.
8.	**Novel entities impact climate change.**	Many novel entities act as greenhouse gases or cause other alterations to the Earth's chemical balance.

9. **Biosphere integrity and land-system change impact each other.**

Changes to land systems can lead to the degradation or loss of natural habitats for species. Changes in biodiversity and the loss of species can have ecosystem-wide impacts, potentially resulting in the shift of land use through ecosystem collapse, which in turn impacts further loss in biosphere integrity.

10. **Biosphere integrity and biogeochemical flows impact each other.**

Atmospheric nitrogen can result in changes to species composition over time, as well as impact their habitats. Changes to the amount of available nitrogen can also influence ecosystem productivity and biological diversity. Eutrophication from excess nutrient inputs into waterways can also threaten aquatic life in localized areas. As biogeochemical flows rely on both non-living and living components of the environment, changes in biosphere integrity could impact the large-scale cycling of nutrients through the environment.

11. **Atmospheric aerosol loading impacts biosphere integrity.**

Just as atmospheric aerosol loading can cause medical complications in humans, it can also cause damage to animals. Aerosols can also block sunlight and limit plants' ability to grow as well as alter cloud formation and precipitation patterns that species rely on.

12. **Stratospheric ozone depletion impacts biosphere integrity.**

Stratospheric ozone causes increased UV rays hitting the Earth's surface, which can cause cancer and immune system issues in humans and animals. Increased UV rays can also limit plant growth and reproductive rates, as well as limit the productivity and reproductive abilities of marine ecosystems, potentially leading to food system weakening.

13. **Ocean acidification impacts biosphere integrity.**

Ocean acidification limits the ability of some aquatic species to build shells or skeletons and has impacts on the physiological development of marine organisms.

14. **Biosphere integrity and freshwater use impact each other.**

Freshwater systems support at least 100,000 species, and the majority of water supplies to major cities come from regions with high biodiversity value. When freshwater sources are overused, polluted or modified, they contribute to the destruction and degradation of habitats for these species, limiting their ability to survive. Biodiversity, particularly richness in the types of algae, plays a vital role in maintaining the health of water systems and cleaning up pollutants in water systems.

15. **Novel entities impact biosphere integrity.**	Pollution caused by novel entities can impact the health and survival rates of different species, as well as damage their habitats. Genetically modified organisms alter the genetic diversity of the biosphere and may outcompete native species.
16. **Land-system change and biogeochemical flows impact each other.**	Agriculture is the primary driver of land-system change, and this conversion often increase the use of nitrogen and phosphorus-based fertilizers. As the biogeochemical cycles move through the living and nonliving components of the environment, significant changes to land-system, such as deforestation, can disrupt the flow of nutrients through the environment.
17. **Land-system change and atmospheric aerosol loading impact each other.**	When forests or other land systems are burned, they emit aerosols into the atmosphere. Atmospheric aerosols can alter cloud formation and precipitation patterns, leading to the spread of desertification.
18. **Land-system change and freshwater use impact each other.**	Forests play a significant role in regulating regional and global water cycles, and deforestation can lead to decreases in rainfall. Without access to water, land systems may be converted to deserts and agricultural systems can fail.
19. **Land-system change and novel entities impact each other.**	Specific land-use changes, such as the conversion of forests to agricultural land, increase the number of novel entities used on the land. Pollution of the land and soil from novel entities, including microplastics, can damage the health of and impact the functioning of entire ecosystems, potentially shifting land systems.

20. **Biogeochemical flows impact ocean acidification.**	Algal blooms caused by excess nutrient inputs release carbon dioxide when they die, causing increased acidification.
21. **Biogeochemical flows and freshwater use impact each other.**	Excess nutrient inputs can cause eutrophication and algal blooms in freshwater systems. Freshwater systems are often used as carriers for nitrogen and phosphorous.
22. **Novel entities impact biogeochemical flows.**	Novel entities include human-made chemicals as well as "naturally occurring elements mobilized by anthropogenic activities." Nitrogen fertilizer for agriculture use relies on ammonia produced from the Haber-Bosch process, an artificial and human-made nitrogen fixation process.
23. **Ocean acidification impacts atmospheric aerosol loading.**	Increased ocean acidification leads to the increased production of a sulphur-based atmospheric aerosol.
24. **Atmospheric aerosol loading impacts freshwater use.**	Atmospheric aerosols can cause changes in cloud formation and precipitation patterns, impacting the availability of freshwater in certain regions.
25. **Novel entities impact atmospheric aerosol loading.**	Many atmospheric aerosols are considered novel entities due to their artificial composition and the human influence that results in their emission into the atmosphere.
26. **Novel entities impact stratospheric ozone depletion.**	Most ODSs are considered to be novel entities.
27. **Novel entities impact freshwater use.**	Novel entities can cause pollution in freshwater systems.

Boundary Interactions Visualization

This information on boundary interactions was used to create the second visualization (Figure 5). Visualizing the boundary interactions is useful to understand the interconnectedness of the Earth System and highlights how degradation in one boundary can lead to impacts across the entire Earth System.

An interactive version of this visualization, made using the systems-mapping program Kumu, can be viewed at http://bit.ly/2YghvzX. Instructions on how to navigate this visualization in Kumu can be found in Appendix B - Visualization Links and Instructions.

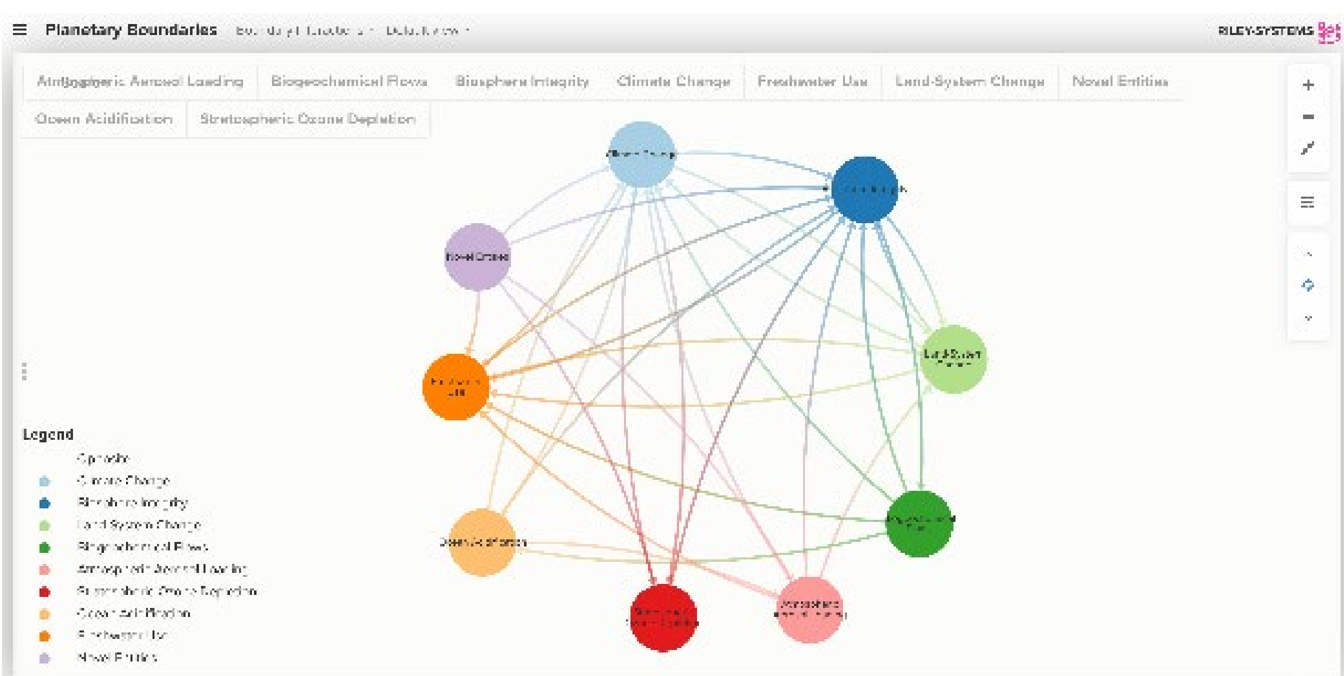


Figure 5. *Still image of the boundary interactions visualization.*

Discussion and Conclusion

5

Discussion

The act of aggregating information on each boundary and visualizing the systems operating between them and the human dimensions of the Earth System allows the reader to begin to conceptualize the complexity of the Earth System.

Visualization 1 - Boundary Influences demonstrates the interconnectedness of the human and environmental dimensions within the Earth System, showing how some actions play an oversized role in the degradation of the environment. Through exploring the map, the user can begin to understand the relationship between the anthropogenic drivers and environmental pressures, and how they are influencing the planetary boundaries. The user would be able to see that agriculture, for example, is highly influential as it directly connects to six of the planetary boundaries, and when second-order connections are included, it connects to all nine of the planetary boundaries. Industry and manufacturing and resource extraction are similarly well connected. Based on these connections, it is easy to understand that changing the current agricultural model, or the industry and manufacturing and resource extraction models, could act as a leverage point to reduce degradation across all nine planetary boundaries.

By showing only the interactions between the nine planetary boundaries, *Visualization 2 - Boundary Interactions* can act as a summary of *Visualization 1 - Boundary Influences* to demonstrate the underlying complexity and system of the Planetary Boundaries framework. This visualization highlights the high-level systems processes of the framework and begins to demonstrate the interdependencies between the boundaries and the feedback loops that, once triggered, can lead to irreversible or run-away changes to the Earth System. For example, degradation in the climate change boundary can lead to degradation in the land-system boundary, which can cause additional degradation in the climate change boundary.

These interactions create a reinforcing, or positive feedback loop in which once triggered, cannot be stopped. *Visualization 2 - Boundary Interactions* shows this feedback at the level of the boundaries, while *Visualization 1 - Boundary Influences* demonstrates some of the details of this feedback such as how climate change can lead to an increase in extreme weather events, which can destroy forests, leading to a reduction in the amount of carbon dioxide sequestered from the environment. Increased atmospheric carbon dioxide, a greenhouse gas, can worsen the impacts of climate change.

Challenges with the Process

A challenge that persisted throughout the gathering and mapping of the information in this report was the sorting of information at an appropriate level of detail. Alternate approaches were attempted to map the information, such as only including the human actions and their impacts on the boundaries (removing the environmental pressures). However, these approaches left out details and weakened the ability of the user to identify important connections in the system. Furthermore, the categorization and sorting of the different influences and impacts into the eleven anthropogenic drivers and environmental pressures influences the output of the report and the nature of the connections. Using a larger number of more detailed drivers and pressure would have resulted in a more detailed map. That said, as the primary goal of this project was to engage non-academic individuals with Earth System complexity and the impactions of anthropogenic drivers, broader categories were used.

At specific points in my research process, I also encountered challenges with finding the appropriate balance of managing the scientific complexity of the information provided while ensuring that it could still be easily understood. As the goal of this project was to provide an introduction to the Planetary Boundaries framework, I opted to limit the scope of the information to a high-level, rather than explaining the step-by-step biological process underlying the concept. While this meant that the report does not include the exact details of many processes, it allows the content to be manageable in length as well as complexity.

Another challenge I faced was with the representation of the two visual outputs. I wanted to ensure that the visualizations showed the connections between various elements. Various forms of systems mapping were explored throughout the process of this project; stock and flow diagrams were useful for showing the impacts of human activities at varying scales and causal loop diagrams began to show success at highlighting the feedback loops. That said, many of these types of systems maps became overly complicated and difficult to navigate. As a central goal of this project was to present the information in an easy-to-understand way, I instead opted to present the visualizations more straightforwardly while still demonstrating causality only through the use of directed arrows.

The challenge of the short three-month time period of this project presented an additional limitation in my reliance on secondary research; no primary research was used to gather or interpret data In reflection of my process, and if given more time to complete the work, I

would have liked to incorporate primary research to allow for a stronger foundation for the guiding of the project, as well as user feedback on the outputs. Specifically, I would have incorporated primary research in the following ways:

- A focus group or survey at the beginning of my process to understand the intended audience's understanding and perception of the Planetary Boundaries framework.
- Workshops during the process of simplifying the terminology and the categorization of elements to understand how the intended audience understood these groupings.
- A series of iterative workshops during the process of creating the visualizations to ensure usability.

Despite not incorporating these methods into this project, the outputs included in this project could act as a prototype and launching point to further categorize and map the boundaries in a workshop and user-driven setting. The main goal of this future work would be to increase the usability of the final visualization and explore different ways of categorizing and visualizing the information across intended audiences.

Areas for Future Exploration

Although this project is an important first step towards presenting information about the Planetary Boundaries framework beyond its current audience, future work is needed to refine the display of information to make it more accessible and easy to understand for the user. For example, sizing of elements or connections could be introduced to visually display significance across the network.

I am also interested in continuing to explore how this tool can be used to inspire or guide action on the boundaries. In future iterations of the visualizations, I would like to highlight feedback loops, making them easier to identify by the viewer. I would also like to apply a sense of weighting to particular systems. For example, degradation in some boundaries, such as biosphere integrity, may have much more severe impacts on other systems compared to degradation in ocean acidification. This approach would require further research, consultation with subject matter experts, and a quantitative approach to modelling the information. Of particular interest to me is incorporating potential solutions into the visualizations. As I continue to explore the concepts presented in this project, I would like to incorporate potential actions that can be taken to restore or protect some of the boundaries.

I am also interested in further exploring these connections against the United Nations' Sustainable Development Goals (SDGs) framework. Similar work has been completed by Capmourteres et al. and Kate Raworth,[168] although both offer reduced approaches to one of the two frameworks. With an understanding of the interconnections between the SDGs the Planetary Boundaries framework can provide an understanding of how we can progress on both societal conditions and planetary health. For example, progress on *SDG 2 - No Hunger* may increase agricultural output, which my research found to be a driving force in the degradation of many of the key systems. Connecting the two frameworks could provide an understanding of trade-offs and synergies that can be used to ensure that progress moves forward for both society and the environment.

Conclusion

The Planetary Boundaries framework outlines the limits to the Earth's ability to sustain human life and highlights the damage caused to the Earth System by human actions. By mapping the interactions between and among the human and environmental dimensions of the Earth System, this project begins to demonstrate the complexity of the Earth's natural system and humanity's role in it. It highlights the delicate balance of environmental conditions that allow humans to live comfortably on this planet. The act of aggregating information on and mapping the human influences across the boundaries also highlights the human activities that are causing the most degradation to this balance and highlights areas in which adaptive or mitigative actions could have the most positive influences.

The two visualizations created by this project demonstrate the need for a systems approach to solving the current environmental crisis. The complexity and interconnectedness portrayed in them not only depict how human activity is intertwined with the natural environment, but it also highlights how human and environmental systems work in tandem in ensuring that the Earth is habitable for human life. The visualizations are useful to demonstrate how we might start to take action towards a more sustainable, or even regenerative, way of living, in which human actions are no longer causing damage to the Earth System, but respecting and restoring the balance that has allowed us to thrive.

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Appendices

Appendix A: Detailed Information on the Planetary Boundaries

This table provides in-depth information about each of the nine key systems featured in the Planetary Boundary framework, and is taken from Steffan et al. (2015).

Climate Change

Control Variables

(a) Atmospheric carbon dioxide concentration, ppm
(b) Energy imbalance at top-of-atmosphere, W m^{-2}

Planetary boundary (zone of uncertainty)

(a) 350 ppm carbon dioxide (350-450 ppm)
(b) +1.0 W m^{-2} (+1.0-1.5 W m^{-2})

Current value of control variable

(a) 398.5 ppm carbon dioxide
(b) 2.3 W m^{-2} (1.1-3.3 W m^{-2})

Biosphere Integrity

Control Variables

(a) Genetic diversity: Extinction rate
(b) Functional diversity: Biodiversity Intactness Index (BII)

*Note: These are interim control variables until more appropriate ones are developed.

Planetary boundary (zone of uncertainty)

(a) <10 E/MSY (10-100 E/MSY) but with an aspirational goal of ca. 1 E/MSY (the background rate of extinction loss). E/MSY = extinctions per million species-years.
(b) Maintain BI at 90% (90-30%) or above, assessed geographically by biomes/large regional areas (e.g. southern Africa), major marine ecosystems (e.g., coral reefs) or by large functional groups.

Current value of control variable

(a) 100-1000 E/MSY
(b) 84%, applied to southern African only

Land-System Change

Control Variables

(a) Global: Area of forested land as % of original forest cover.
(b) Biome: Area of forested land as % of potential forest

Planetary boundary (zone of uncertainty)

(a) 75% (75-54%) Value are weighted average of the three individual biome boundaries and their uncertainty zones.
(b) Tropical: 85% (85-60%); Temperate: 50% (50-30%); Boreal: 85% (85-60%)

Current value of control variable

(a) 62%
(b) n/a

Biogeochemical Flows

Control Variables

(a) P Global: P flow from freshwater systems into the ocean
(b) P Regional: P flow from fertilizers to erodible soils
(c) N Global: Industrial and intentional biological fixation of N

Planetary boundary (zone of uncertainty)

(a) 11 Tg yr^{-1} (11-100 Tg yr^{-1})
(b) 6.2 Tg yr^{-1} mined and applied to erodible (agricultural soils) (6.2-11.2 Tg yr^{-1}). Boundary is a global average but regional distribution is critical for impacts.
(c) 62 Tg yr^{-1} (62-82 Tg yr^{-1}). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth System, but regional distribution of fertilizer N is critical for impacts.

Current value of control variable

(a) -22 Tg yr^{-1}
(b) -14 Tg yr^{-1}
(c) -150 Tg yr^{-1}

Atmospheric Aerosol Loading

Control Variables

(a) Global: Aerosol Optical Depth (AOD), but much regional variation
(b) Regional: AOD as a seasonal average over a region. South Asian Monsoon used as a case study.

Planetary boundary (zone of uncertainty)

(a) n/a
(b) (South Asian Monsoon as a case study): anthropogenic total (absorbing and scattering) AOD over Indian subcontinent of 0.25 (0.25-0.50); absorbing (warming) AOD less than 10% of total AOD

Current value of control variable

(a) n/a
(b) 0.30 AOD, over South Asian region

Stratospheric Ozone Depletion

Control Variables

Stratospheric ozone concentration, DU

Planetary boundary (zone of uncertainty)

<5% reduction from pre-industrial level of 290 DU (5-10%), assessed by latitute

Current value of control variable

Only transgressed over Antarctica in Austral spring (~200 DU)

Ocean Acidification

Control Variables

Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite

Planetary boundary (zone of uncertainty)

Greater than or equal to 80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (greater than or equal to 80-70%)

Current value of control variable

~84% of the pre-industrial aragonite saturation state

Freshwater Use

Control Variables

(a) Global: Maximum amount of consumptive blue water use ($km^3\ yr^{-1}$)

(b) Basin: Blue water withdrawal as % of mean monthly river flow

Planetary boundary (zone of uncertainty)

(a) 4,000 $km^3\ yr^{-1}$ (4000-6000 $km^3\ yr^{-1}$)

(b) Maximum monthly withdrawal as a percentage of mean monthly river flow. For low-flow months: 25% (25-55%); for intermediate-flow months: 30% (30-60%); for high-flow months: 55% (55-85%)

Current value of control variable

(a)~2,600 $km^3\ yr^{-1}$

(b) n/a

Novel Entities

Control Variables

No control variable currently defined

Planetary boundary (zone of uncertainty)

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

Appendix B: Visualization Links and Instructions

Link to *Visualization 1 - Boundary Influences*: http://bit.ly/38gD6Nk
Link to *Visualization 2 - Boundary Interactions*: http://bit.ly/2YghvzX

Both visualizations were made in the systems-mapping program Kumu. The visualizations are designed for the user to be able to interact with them to find learn more or to sort information by each key system in the Planetary Boundaries framework. The visualizations are viewable in the following browsers: Chrome, Safari, Firefox, Internet Explorer 11, and Microsoft Edge. In the visualizations, elements refer to the circle nodes, while connections refer to the arrows between each element.

Showcasing

By hovering over an element, the user can showcase it by fading all other elements and only displaying the elements and connections that are directly neighbouring the selected element.

Focusing

If an element is clicked on, the user can choose to “focus” on that element by clicking the Focus button near the middle of the right hand side of the display. This highlights only the elements that are a first-level connection with the selected element. By clicking the arrows above and below the focus button, the user can zoom in or out on this element to view additional levels of connections, such as secondary and tertiary connections.

Sorting

In both visualizations, the user can click the name of a boundary located at the bottom or top of the map to show only the connections and elements that play a role in the operation of that boundary’s processes. All elements and connections not related to the selected boundary will move to the outside of the screen. Multiple boundaries can be selected at once.

Accompanying Items

Visualization 1 - Boundary Influences: The Kumu map demonstrating the network of boundary influences. December 2019. http://bit.ly/38gD6Nk

Visualization 2 - Boundary Interactions: The Kumu map demonstrating the interactions between the nine planetary boundaries. December 2019. http://bit.ly/2YghvzX