A safe operating space for New Zealand/Aotearoa

Translating the planetary boundaries framework

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Purpose of this report

The purpose of the report is to translate the planetary boundaries framework for New Zealand to inform government approaches to environmental stewardship, well-being and economic development.

- The planetary boundaries framework provides an international and long-term context for national policy setting. It can be used as a benchmark for measuring progress towards environmental goals.
- The framework provides a systems view that integrates a range of environmental challenges from climate change and biodiversity loss to nitrogen usage and deforestation.
- The translation approach adopted in this report explores New Zealand's territorial environmental impact in relation to planetary boundaries and its impact beyond national boundaries due to, for example, consumption of products produced elsewhere.

In these respects, the analysis provides a global systemic perspective to inform policy.

Foreword

We all want a strong, stable economy, greater health and well-being, and to ensure a bright future for the next generation. This is within our grasp. The foundation is a resilient natural environment. But the environment is currently losing its resilience. This is happening at a local level as water quality deteriorates in lakes and rivers or as species become extinct. It is also happening at a global level as the climate changes, the oceans become more acidic and chemicals destroy the ozone layer.

Decisions made now and in the coming years will have far-reaching impacts on the local and global environment for decades and centuries. In turn, this will have far-reaching implications for the long-term resilience of social-ecological systems. Now is the moment to put societies and economies on a trajectory towards intergenerational prosperity. Many nations are trying to figure out how to move onto this pathway.

This report, *A safe operating space for New Zealand/ Aotearoa*, emerged from conversations with James Shaw, Minister for Climate Change, Minister of Statistics and Associate Minister of Finance, and Vicky Robertson, Secretary for the Environment. We discussed three things: The opportunities for New Zealand of building resilient societies based on regenerating natural resources; New Zealand's unique biological diversity, cultural diversity and diversity of landscapes are the foundation of the country's economic strengths; but also that many of the challenges facing New Zealand are interconnected and require a systems view of the solutions.

What do we mean by a systems view? We should not think of climate change, biodiversity and water quality as separate environmental challenges competing for resources. Nor should we see wellbeing, the environment and the economy as independent from each other. Most of the challenges we face are linked. They are linked across scales from the local up to the global, and across economic sectors – from agriculture to finance and health, and across regions – consumption in one country leads to deforestation or other resource depletion elsewhere. By taking a systems view societies can make better informed decisions.

In 2009, my colleagues and I published the Planetary Boundaries framework to provide an initial science-based assessment of interconnected risks at the global level. In the last decade, we have worked with other colleagues to translate and downscale this framework to make it relevant at a national level for example for Finland, Germany, the Netherlands and Sweden. Most recently the European Environment Agency has published an analysis of a "safe operating space" for Europe (April 2020).

This report builds on these assessments. It quantifies five of the nine planetary boundaries relevant to New Zealand, New Zealand's contribution to boundary transgressions and it allows comparisons with other countries. This follows the maxim "You can't manage what you can't measure". Like all developed nations assessed, New Zealand exceeds its fair share of the safe operating space related to climate, biodiversity, nutrient use and deforestation. However, science is increasingly providing evidence that it is feasible to reduce pressure on the planet and economically prosper. Indeed, we can go further and say that it is possible to build a regenerative, circular economy that enhances New Zealand's resilience while at the same time reducing the transgression of planetary boundaries and thus providing more opportunities for the coming generations than previous generations.

We hope this report provides a starting point for broader scientific and stakeholder discussions that look at targets related to, for example, the climate, health and biodiversity benefits of reforestation or improved nutrient management.

Ultimately, this is a discussion about stewardship – what kind of world do we want our children to inherit? New Zealand's unique cultural diversity has contributed to new ways of thinking about stewardship, for example, endowing the Whanganui river and Taranaki mountain with personhood in the eyes of the law. We hope this report helps catalyse new conversations around stewardship of the global commons.

Johan Rockström, April 2020
Director, Potsdam Institute for Climate Impact Research
Edmund Hillary Laureate

Executive summary

Planetary boundaries

Human pressure on Earth's life support system has grown exponentially in the last 70 years. This pressure is now threatening the resilience of the Earth system.

In 2009, researchers identified **nine** key variables that affect Earth's life support system. For these key variables they identified boundaries beyond which sustaining the life-support system in a healthy state is at risk. This is the planetary boundaries framework. In 2015, scientists assessed that four of the nine boundaries have been transgressed to date. These relate to climate, biodiversity, land use and use of fertilisers (environmental flows of nitrogen and phosphorus). Transgressing boundaries increases the risk of crossing tipping points in the Earth system, for example, related to collapse of the West Antarctic Ice Sheet or Amazon rainforest.

The planetary boundaries framework provides a systemic, long-term view of environmental modification, degradation and resource use. It delineates a precautionary "safe operating space" for multi-generational sustainable development. That is, if all economies aim to reduce pressure on transgressed planetary boundaries this will help ensure a long-term sustainable planet for future generations. Doing so brings many benefits including economic stability, improved health, food security, cleaner water and less air pollution.

The planetary boundaries framework provides a quantitative assessment of the required global level of ambition to meet the Sustainable Development Goals. By bringing globally systemic perspectives on national production-based and consumption-based environmental impacts it can inform New Zealand's current national policies and target-setting under the 2030 Agenda.

Translating planetary boundaries for New Zealand

- Since first publication in 2009, several countries and the European Union have translated or "downscaled" the framework including Sweden, Finland, Germany and the Netherlands.
- There are several ways to translate the boundaries. The method adopted most commonly, and used in this analysis, is known as equal per capita-based "fair share": a nation's allocation is based on the size of the population compared with the global population.
- For New Zealand, we assessed the national pressure on planetary boundaries in two ways. From a production-based perspective accounting for all resource use and emissions within New Zealand and from a consumption-based perspective accounting for the resource use and emissions anywhere in the world related to the total consumption of goods and services by New Zealanders.
- Five boundaries were assessed (Figure 1). These were selected based on suitability for translation to the national scale and data availability: climate change, land-system change, freshwater use, biogeochemical cycles (nitrogen and phosphorus use) and biosphere integrity (related to biodiversity). Boundaries not assessed: novel entities, ocean acidification, aerosol loading, ozone depletion.

Results

Like other high-income nations that have been assessed, New Zealand exceeds its fair shares of the five planetary boundaries. The transgressions apply for both consumption-based and production-based perspectives, based on the equality principle and translated per capita or per area, depending on the boundary. Other allocation principles and methods may yield different outcomes.

Sustainable solutions exist to significantly reduce pressures on planetary boundaries. Reducing these pressures will also support regeneration of New Zealand's natural capital for long-term economic prosperity.

Climate change

New Zealand exceeds its national share of the global climate boundary by over a factor of 5 for production-based emissions, and over a factor of 6.5 for consumption-based emissions. Boundary transgression is assessed based on the remaining global carbon budgets (CO_2 emissions only) for 1.5°C and 2°C warming. These were translated to the national scale with different approaches for allocating the global budget (equal-per capita allocation, business as usual, and exponential reduction) over two time horizons (2050 and 2100). The current per capita emission rate of the average New Zealander, 7.3 tonnes (tCO_2 cap yr^{-1}), exceeds the emission rate required to avoid transgression (1.85 tCO_2 cap yr^{-1}). Annual emissions are currently around 35 million tonnes ($MtCO_2$). If these rates continue, New Zealand's share of the global carbon budget associated with the 2°C warming guardrails will be exceeded in 2038.

Land-system change

New Zealand exceeds its national share of the land- system change boundary by a factor of 1.25. Boundary transgression is assessed based on what remains of potential forest extents. We assessed the degree of land-system change based on two metrics, i) the fraction of land converted to cropland and ii) the fraction of natural forest cover remaining. The initially proposed planetary boundary, published in 2009, required the conversion to cropland not to exceed 15% of total land area. By this metric, New Zealand is still in the safe operating space because its high percentage of pastureland (40%) is excluded from the analysis. The revised 2015 assessment of planetary boundaries introduced the maintenance of biome-level natural forest cover as a metric. More than half (55%) of New Zealand's original forest cover has been removed. The planetary boundary for temperate forests is set at 50% maintenance of the natural forest cover, which New Zealand transgresses.

Freshwater

New Zealand exceeds its fair share of the global freshwater boundary by a factor of 1.9 for production-based water use and 2.1 for consumption-based water use. Boundary transgression is assessed based on direct use of "blue" water from rivers, lakes, reservoirs and renewable groundwater, such that sufficient "green" water is available for terrestrial and aquatic ecosystem functioning. The country has abundant freshwater resources so water quality issues are likely more pressing than water quantity concerns, though water quality issues are often exacerbated by water quantity fluctuations. In view of the widely varying local contexts, analysis on a catchment by catchment basis will be necessary to support long-term sustainable water use. Globally, water availability and uncertainty will be defining issues of the 21st century. New Zealand should plan to build long-term resilience into its own water systems and at the same time reduce its pressures on external and global water resources, in particular in water-stressed regions.

Biogeochemical flows

New Zealand's greatest transgressions of its fair share of the planetary boundaries relate to the nitrogen (N) and phosphorus (P) boundaries by factors from 4 to almost 55. In both cases, production-based transgressions are higher than consumption-based transgression on account of New Zealand's considerable agricultural net exports. This holds true for both nitrogen and phosphorus applications on cropland, and nitrogen emissions resulting from fertiliser use on all land types and non-agricultural sectors. Local impacts of over-fertilisation are already visible causing growing concerns in agricultural areas regarding water quality, loss of soil quality and eutrophication. The allocation of nitrogen and phosphorus based on population (equal per capita) gives a higher fair share (provides a more generous allowance) for New Zealand than allocation based on current cropland extent (equal per area). The magnitude of the production-based transgression is a result of these allocation metrics, where New Zealand has low population density and relatively small amount of cropland as opposed to pastureland. This highlights a limitation of these metrics and the need for improved globally harmonised data on agricultural lands.

Biosphere integrity

New Zealand exceeds its national share of the global biosphere integrity boundary by a factor of 3.4. Boundary transgression is assessed based estimates of biodiversity intactness, using an index for species abundance. The higher the score the more resilient the ecosystem. New Zealand averages 58% compared with the global average of 75%. Nationally, the highest value is 85% intactness of species abundance maintained. Some areas have been degraded down to 28% maintained. The planetary boundary is set conservatively at 90%, but with a large uncertainty range of 30-90%. Taken together with the forest cover boundary transgression, it is clear that land-use change has greatly impacted biodiversity. Although the global consequences of such national transgressions of the boundary are uncertain, biodiversity is an essential foundation for maintaining the resilience of ecosystems, biomes and ultimately the Earth system, and hence also for people's well-being.

Figure 1: Five planetary boundaries translated to New Zealand. The radial plot shows national transgression of five planetary boundaries on a normalised scale. New Zealand exceeds its "fair share" of the global safe operating space for most production-based (territorial) and consumption-based boundaries. The safe zone is depicted in the centre, where the edge of the green circle is the normalised boundary (= 1). After boundary transgression is a zone of increasing but uncertain risks (= 1 - 2). Beyond this is a zone of high risk, depicted by the red line (= 2), which equates to a boundary transgression by a factor of 2. From the red line outward, factors of transgression continue approximately according to the white lines. The scale is capped at a factor of 15.

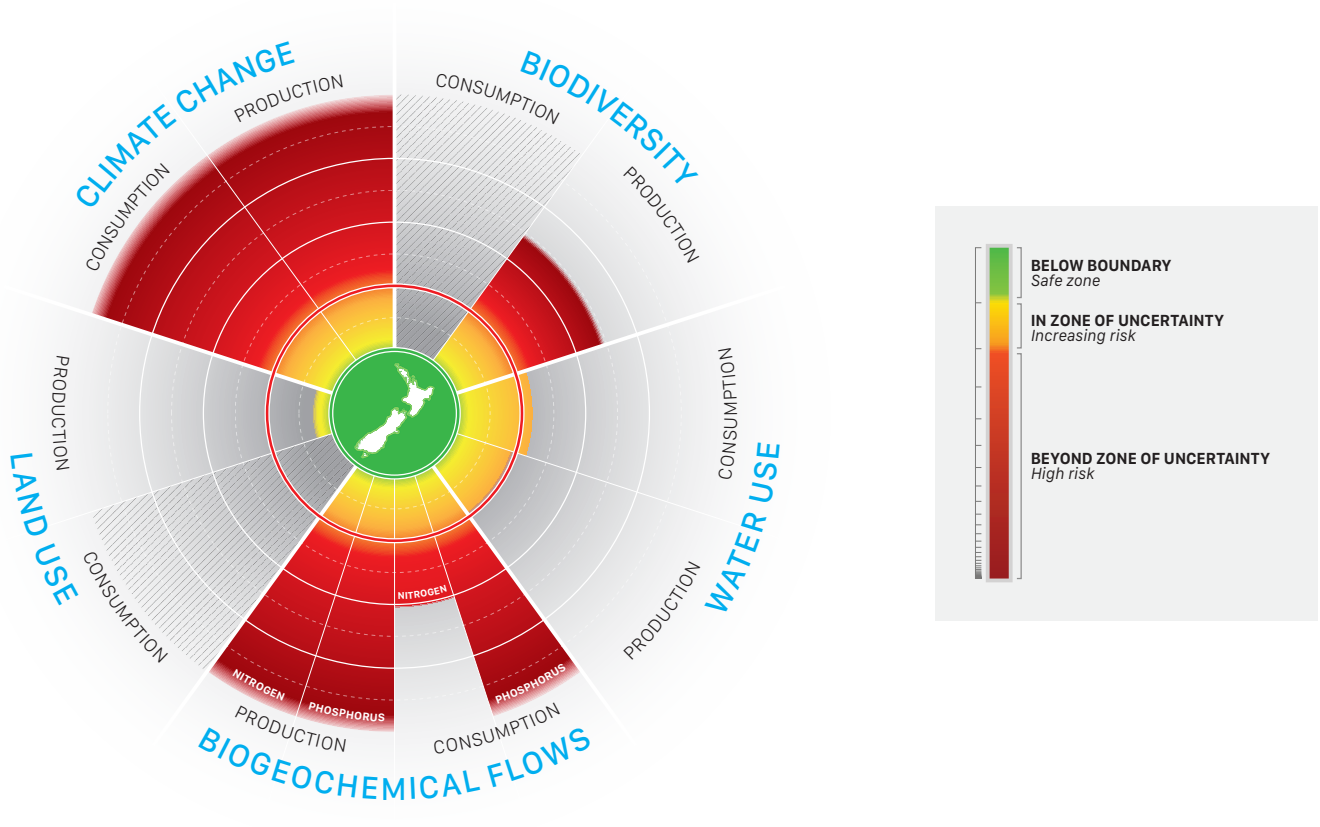
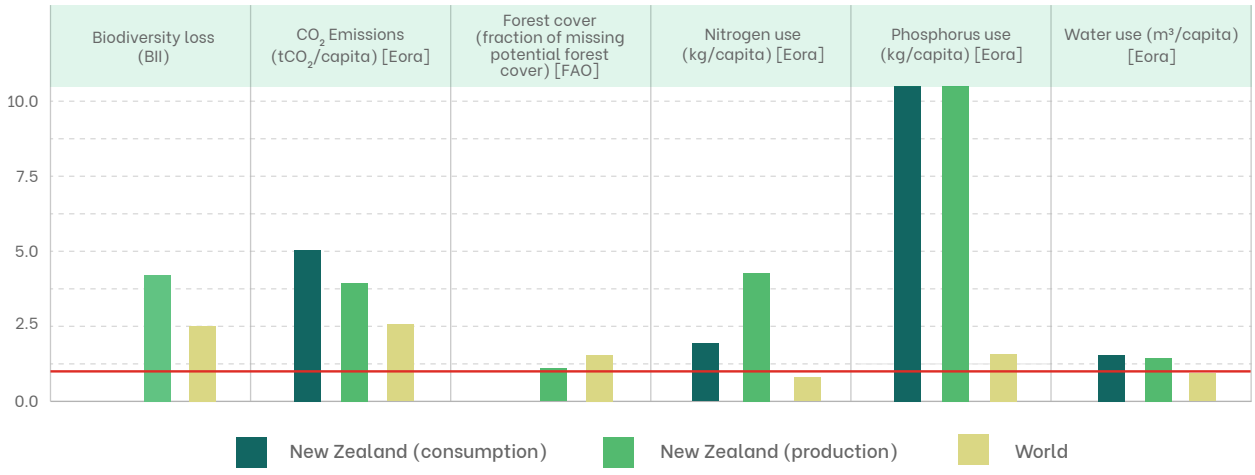


Figure 2: New Zealand's national consumption-based and production-based performance compared with the global average. The red line marks the normalised planetary boundary (translated to national shares), set at 1 on a common scale of 0–10 to allow comparison. The safe operating space is under 1, over 1 marks a transgression of the boundary.



New Zealand's food system: a sector case study

The way food is produced, consumed and wasted globally is placing a heavy burden on the environment. Accordingly, improvements to food systems can be one of the most powerful levers for reducing environmental impacts. We assessed aspects of New Zealand's food production and consumption as a case study for the required sustainability transition at national level and to support sustainable food systems on a resilient planet. We explored the current state of environmental impacts of the New Zealand food system and projected impacts for 2050 based on current trends ("business as usual"). The food system analysis complements the main analysis by providing a deeper dive into the food and agricultural sectors using a global food system model and framework for analysis. The similarities and differences between the food system analysis and planetary boundary analysis are further elaborated.

Translating global assessments of food system sustainability to national levels is complex, and there is no single correct way to adapt global food-system targets to New Zealand. Achieving an environmentally sustainable food system will require trade-offs, and tackling these trade-offs will involve normative decisions, necessitating dialogues among stakeholders. This preliminary assessment of New Zealand's "safe operating space" for food systems offers one analysis to help inform such a process.

Key findings

Production

- Dairy and livestock production dominate the New Zealand agricultural sector and dominate the food sector's contribution to climate change. This economically important sector will play a key role in New Zealand's journey towards a safe operating space. For example, New Zealand's production-based emissions of methane and nitrous oxide from food production (39 $MtCO_2$-eq) in 2010 (the baseline year of analysis in the food system analysis) were more than ten times over the sustainable level of carbon dioxide equivalents (CO_2-eq) based on a global equal per capita distribution. By 2050, this would rise to 55 $MtCO_2$-eq on a global "business as usual" trajectory. (NB this does not account for specific policy actions at a national level).

- The food system analysis highlighted that other environmental impacts of production will also need to be addressed. In 2010, New Zealand's food production reached the country's fair share of the boundary for phosphorus application, and without intervention it is projected to transgress the boundary by 2050. We discuss this finding in light of the estimates found in the planetary boundary analysis.

Consumption

- New Zealand's current and projected food-related impacts (i.e., in 2010 and 2050) are within the boundaries for cropland use, blue-water use and nitrogen application.

- However, for climate, in 2010, New Zealand's food consumption led to approximately 1 million tonnes more CO_2-eq than would be considered sustainable. Beef and lamb accounted for most consumption-based emissions (35% and 45% of total CO_2-eq, respectively). By 2050, on current trajectories, New Zealand would generate double the amount of CO_2-eq through food consumption than would be considered sustainable.

Supporting evidence-based policymaking

- This preliminary assessment encountered several important gaps that signal more resourcing is needed to define food system targets jointly by scientists and policymakers and to use these targets to benchmark the performance of New Zealand food systems.

- Data constraints mean that further work is needed to develop more robust and comprehensive food-system targets. For example, the proposed nitrogen boundary focuses on nitrogen application rates and does not capture all sources of reactive nitrogen. Similarly, the boundary for cropland may benefit from extending to include an estimate of sustainable pastureland.

- Food systems are much more than the environmental impact of what people produce and consume. They are linked to nearly all aspects of well-being and sustainable development and should be integrated into New Zealand's wider policy context. For example, links between food policy and the Living Standards Framework could ensure that multiple dimensions of well-being are supported.

Operationalising planetary boundaries in New Zealand

This report provides the first quantitative assessment of a "safe operating space" for New Zealand based on a per capita "fair share" - a standard scientific approach for exploring global environmental resources or global commons. If all countries adopted a "fair share" approach this would support long-term Earth system stability. Such an approach also supports regeneration of New Zealand's natural capital for long-term prosperity.

Aligning national environmental policies with global frameworks is a political process involving normative decisions regarding equity, responsibility, ability to act, risk, allocation of resources and precaution. Science can support this process by providing quantitative assessments

of interdependent environmental pressures and frameworks for risk management under uncertainty.

Interpretation of the results for policymaking is nuanced because each boundary is set differently and translation has to be based on context-dependent assumptions. It is too simplistic to say, for example, that the "safe operating space" boundary for nitrogen should determine a near-term target or an absolute limit for New Zealand. However, the global boundary can add value to existing national targets by providing information on global scale sustainability requirements with respect to anthropogenic reactive nitrogen production. This report therefore also highlights potential links to New Zealand's national and international policy.

Next steps

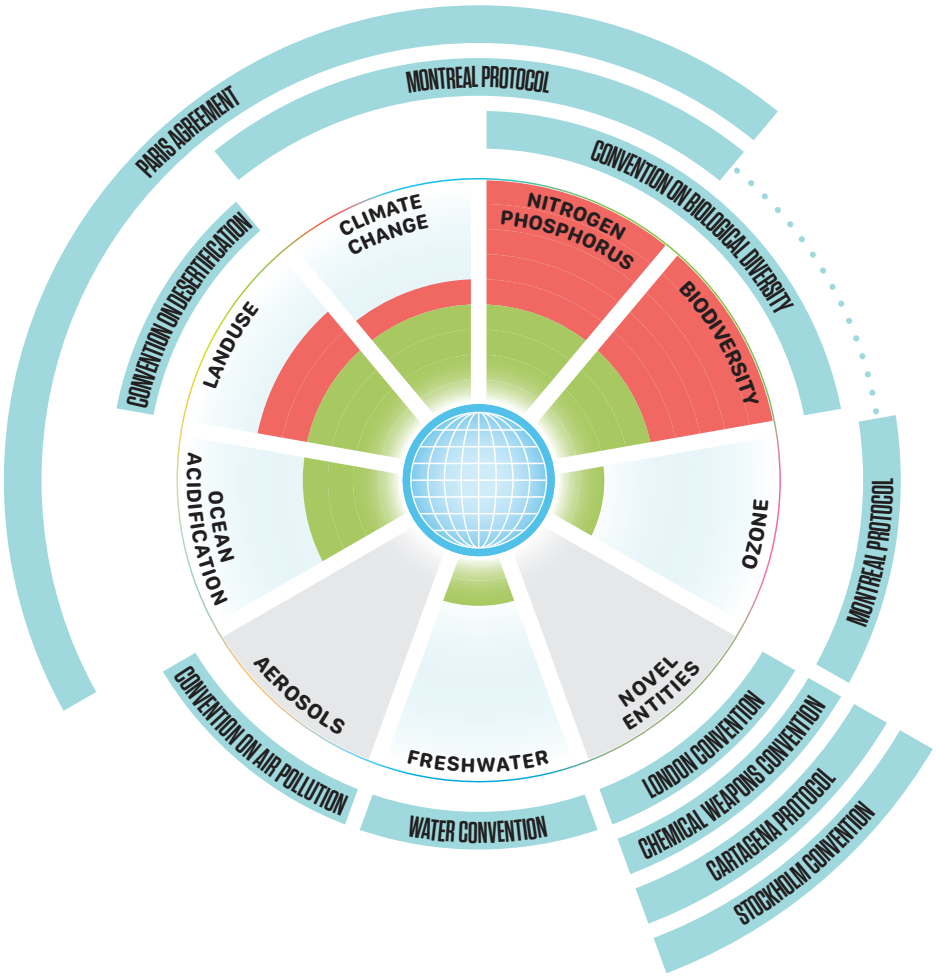
Several countries have commissioned similar analyses based on the planetary boundaries framework. These analyses allow countries to use a systems view to assess their global environmental responsibilities. The most recent assessment was published by the European Environment Agency in April 2020. These assessments highlight where there are structural gaps between global ambitions of multilateral environmental agreements and national policies (Figure 3). These assessments also highlight knowledge and data gaps. The following research and translation priorities need to be addressed:

- National downscaling and translation initiatives have been led by environment ministries and academic institutions. We have observed less engagement with other ministries and relevant stakeholders. A systems view of the challenges and opportunities requires new engagement processes across sectors and ministries.

- Further development of principles, methods and parameterisations for allocating the global safe operating space to individual countries or regions, including normative decisions about acceptable risks and fair shares;

- Harmonisation of national and international data, for the analyses of national fair shares and their transgression, in particular consumption-based footprints;

Figure 3: A systems view of international policy (outer rings) related to planetary boundaries.



- Interpretation and contextualisation of global issues at the local scale (that is, sub-national level) and vice versa requires top-down/bottom-up integration of targets;

- Rapidly changing environmental conditions, pressures and knowledge require dynamic national assessments that account for these changes;

- More work is needed to link positive economic and well-being outcomes from reducing environmental impacts related to planetary boundaries;

- National target-setting and development of underlying relevant knowledge is a co-development process, involving scientists and policymakers, which requires new ways of visualising and communicating scientific information and knowledge.

Chapter 1

A planetary perspective

1.1 Global environmental stability under pressure

National decision-making often focuses on immediate short-term priorities but in today's globalised world it is increasingly important to take a long-term, large-scale view. Resource use and damaging waste emissions are high and rising, placing global environmental stability and predictability under pressure. This report sets out how and why a planetary scale and multi-decadal perspective is needed, even for decisions about everyday matters of production and consumption. It focuses on New Zealand as a globally connected nation. It examines the food system as a case study because it is such an important element in New Zealand's global connectivity and highlights the interdependence of social and ecological systems crossing scales from the local to the global.

Placing the current environmental situation in the long-term perspective

Over the last 10,000 years, Earth's climate and ecological conditions have remained remarkably stable. This period is known as the Holocene. Scientific advances relating to how Earth operates as a complex system have now reached a point where boundary conditions to maintain this remarkable stability can be identified.[1, 2] Settlements, agriculture, then civilisations only emerged once environmental conditions settled into relative stability, so the Holocene can be seen as a foundation of human progress and economic development.[3] Without human interference, similar conditions would likely have persisted for a further 50,000 years.[4]

Human activities have a profound impact on the Earth system and are putting this relative stability at risk. Since the 1950s – a single human lifetime – a surge in impact has pushed Earth beyond Holocene boundaries related to climate, natural biogeochemical cycles, biodiversity loss, forest cover and many more parameters. The pressure is increasing on Earth's "life-support systems" for today's societies. Indeed, even though industrial emissions of fossil fuels started to rise in about 1750 with the Industrial Revolution, more than half of emissions have occurred since 1990[5] (Figure 4).

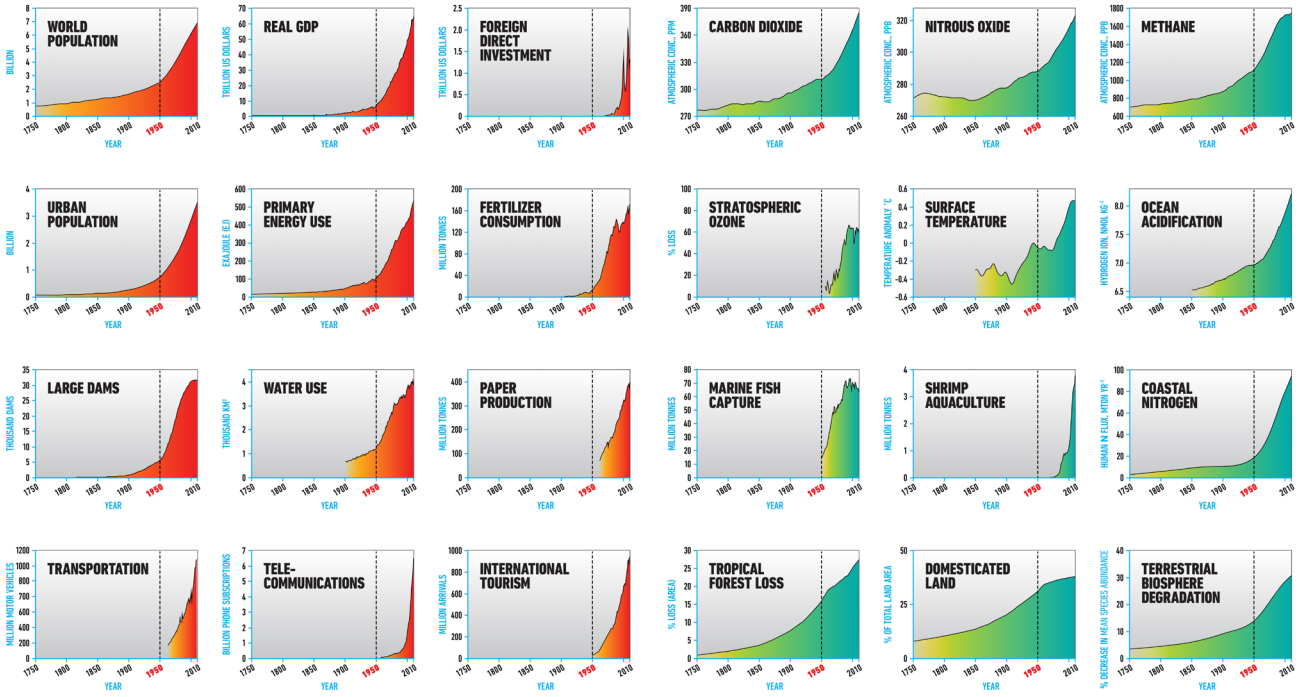
The scale of change set in motion by human activity has led researchers to propose that Earth is no longer in the Holocene. Human activity has pushed Earth into a new geological epoch – the Anthropocene. Environmental impacts in this new epoch are characterised by *speed, scale, connectivity* and *surprise*. Knowledge of these new risks creates new responsibilities; it demands greater international cooperation and forces a re-evaluation of economic models of development.[6, 7]

International environmental governance

Since 1972 and the first United Nations conference on the human environment, international agreements on the environment and sustainable development have been established to foster global cooperation. This culminated in five new agreements in the period 2015–2016: the Sendai Framework for Disaster Risk Reduction; the Addis Ababa Action Agenda; the 2030 Agenda for Sustainable Development (including the Sustainable Development Goals or SDGs); the Paris Agreement on climate; and the New Urban Agenda. Together these agreements form a plan to find a safe operating space for human progress and economic development.

These new international frameworks emphasise proportionate and equitable contributions from all countries and actors towards achieving these goals. Agenda 2030, for

Figure 4: The Great Acceleration in human activity (1750–2015). The left (orange) depicts a representative range of socio-economic activities in the last 250 years. Data on the right (green) represents significant disruption of key Earth-system processes. In both cases the most significant impact occurs post 1950.[5] Image: Globaïa.



example, calls on governments to set their own national targets guided by the global level of ambition but taking into account national circumstances.[8] Defining a national level of ambition should, then, consider a global outlook. But Agenda 2030 and the SDGs do not systematically quantify global environmental targets and leave room for interpretation. More significantly, Agenda 2030 provides no mechanism to translate global environmental goals to the national level. Translation is further complicated by today's globalised world where environmental impacts cross country borders and geographical scales. International trade, for example, increases the spatial separation between production and consumption externalising environmental impacts often across large distances, making countries' full impacts difficult to quantify and trace.

Establishing national environmental targets based on global frameworks is a complex task that requires a political process. It involves normative decisions based on equity, responsibility, ability to act, risk, allocation of resources and precaution. However, science can underpin this process by providing quantitative assessments of interdependent environmental risks and frameworks for risk management under uncertainty. First published in 2009 and updated in 2015, the planetary boundaries framework is the first full Earth-system risk management framework.[9, 10] While designed for Earth-system analysis, a surge in interest at regional, national, city and company scales has led to a wide range of translation approaches to apply the framework at these scales (Table 2). These translation approaches explore different criteria and methods to "fair share" allocations of the global safe operating space.

This report analyses ways New Zealand can align its own national environmental targets with the global framework for long-term Earth-system risk management.

1.2 A shrinking safe operating space for humanity

Because of human activities, the rates of change of all key components of the Earth system are accelerating. One of the most important questions in global change research is will incremental pressure lead to incremental change in the Earth system? Or will vital parts of the system – such as forests, ocean circulation or ice sheets – respond in non-linear and interconnected ways?

The geological record shows that changes on Earth are not always incremental. Earth's history is punctuated with abrupt, rapid shifts whereby incremental change has given way to shock and surprise.

Research is maturing on tipping points, non-linearities, regime shifts and thresholds involving interactions

and feedbacks in the Earth system. In 2008, 15 "tipping elements" were identified, including the Amazon rainforest, permafrost, the West Antarctic Ice Sheet, El Niño and the Asian Monsoon[11] (Figure 5). Each tipping element included a mechanism that could push the system out of a state that reinforces stability and into a state that reinforces instability. This early analysis estimated that these systems are at grave risk of destabilisation if global average temperature rises by 3°C or more above pre-industrial temperatures.

The most recent assessments indicate that the tipping points may be much closer than previously thought. Ice loss is accelerating on the West Antarctic Ice Sheet and it may have already crossed an irreversible tipping point, eventually raising sea levels a further 3 metres.[12,13] The Greenland Ice Sheet may also have crossed a tipping point.[12] Certainly when temperatures reached similar levels in the past, both Greenland and Antarctica partially destabilised, raising sea levels around 6 metres over timescales of centuries or more.[14]

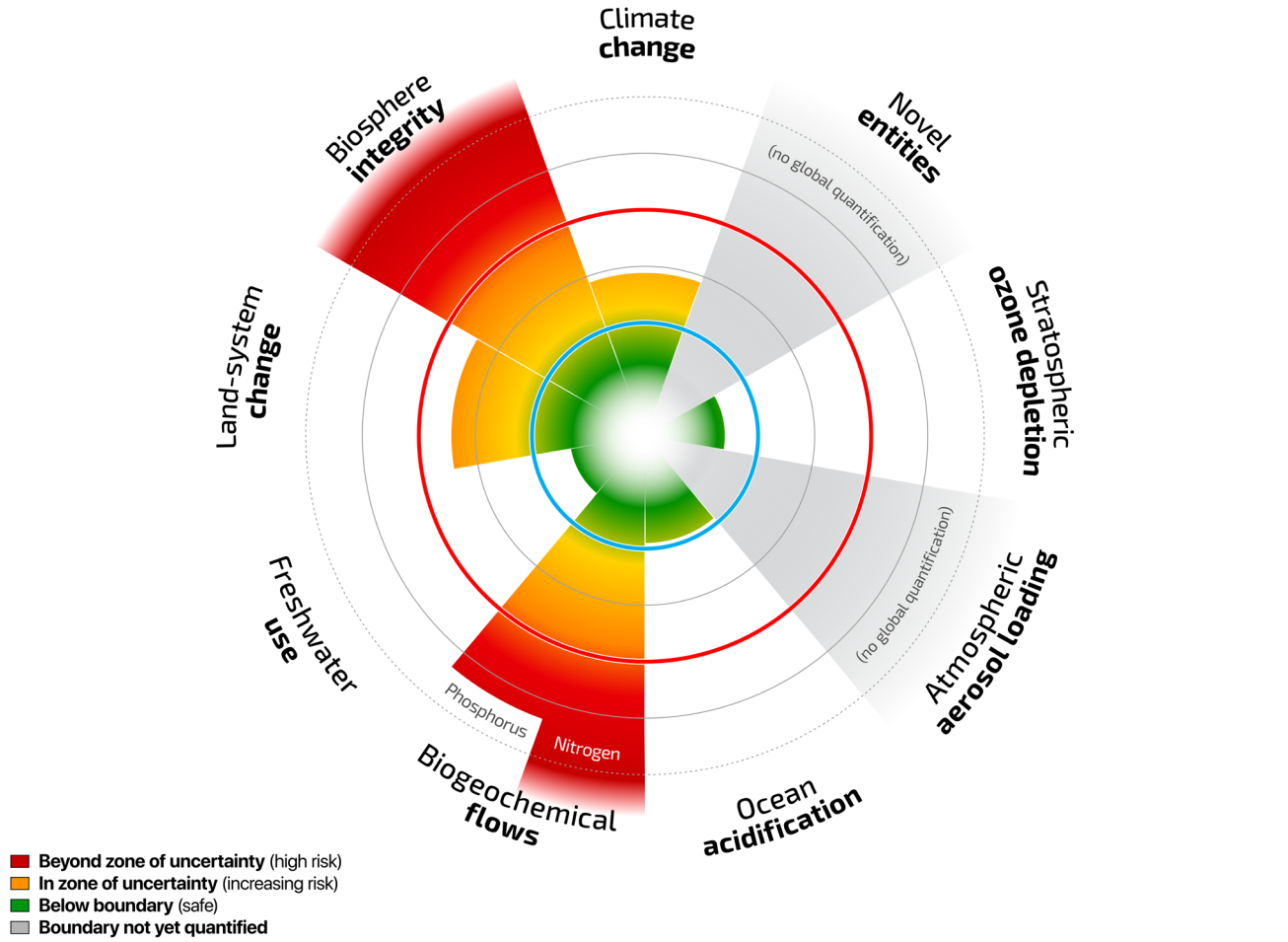
Temperature is not the only critical variable in the Earth system. The Amazon rainforest may reach a tipping point switching from forest to savanna if deforestation reaches 40%, according to earlier estimates.[15] Since the 1970s, the Amazon has shrunk about 17%. Now, some researchers estimate when rising temperatures are also factored in, the tipping point may be much closer, potentially reached at 20–25% deforestation.[16] Recent research shows the Amazon is losing its ability to store carbon and is on course to become a net source of carbon by about 2030.[17]

Beyond climate, recent research analysing 30 types of regime shift – from coral collapse to rainforest to savannah switches – indicates that crossing tipping points in one ecosystem can increase the risk of crossing tipping points in other ecosystems.[18] In this scenario of cascading tipping points, society's efforts to maintain a stabilised Earth could be overwhelmed.[19]

1.3 Introducing planetary boundaries

The planetary boundaries framework emerged from the growing scientific literature on resilience – the ability of a system to bounce back and transform when facing a shock. Very specifically, great strides have been made in this research field in recent decades related to the Earth system and human interactions. Much of this research focuses on interactions, non-linearities and thresholds in the Earth system.

Figure 5: The planetary boundaries framework identifies nine Earth-system processes critical to Holocene-like conditions.[10] Image: Globaïa.



Source: Steffen et al. Planetary Boundaries: Guiding Human development on a changing planet, Science, 16 January 2015. Design: Globaia

Core concepts

Earth system

Earth is a complex, dynamic system, with interacting physical, geological, chemical and biological processes. The physical "components" are land, ice, the oceans and the atmosphere. They influence the flows of heat and water. Earth's natural cycles include carbon, nitrogen, phosphorus, water and many other processes. The Earth system's dynamics have changed through geological time, as a result of changes in internal forcing, such as volcanic and tectonic changes that affect global flows of heat and matter; and external forcing: mainly, changes in the intensity of solar energy reaching Earth. Humanity's social systems are also part of the Earth system and are now the main drivers of planetary change.

Biosphere

The biosphere is defined as all ecosystems on Earth and the zone where life exists. The biosphere is a vital component of the Earth system and influences the natural cycles. Life plays an important role in feedbacks that maintain the stability of the Earth system.

Social-ecological systems

In today's globalised world, societies and economies are fundamentally integrated with the biosphere. The world's ecosystems maintain climate stability and provide water, food, fibres and many other beneficial functions. There are now virtually no ecosystems that are not shaped by people and there are no people without the need for life-supporting ecosystems and the services they provide. A scientific starting point for this report is social-ecological systems.

Resilience

Resilience is the capacity to deal with change and continue to develop. The term applies equally well to social, ecological and social-ecological systems. Ecosystem resilience is a measure of how much disturbance (like storms, fire or pollutants) an ecosystem can handle without shifting into a qualitatively different state. It is the capacity of a system to both withstand shocks and surprises and to rebuild itself if damaged. Social resilience is the ability of human communities to withstand and recover from stresses, such as environmental change or social, economic or political upheaval. Resilience in societies and their life-supporting ecosystems is crucial in maintaining options for future human development.

Figure 6: Currently active tipping elements in the Earth system. In 2008, 15 tipping elements were identified. In 2019, empirical evidence indicates many of these potential tipping elements are changing at unprecedented speeds and scales. Some may recently have crossed tipping points, for example, the West Antarctic Ice Sheet. Several tipping elements are connected.[12]

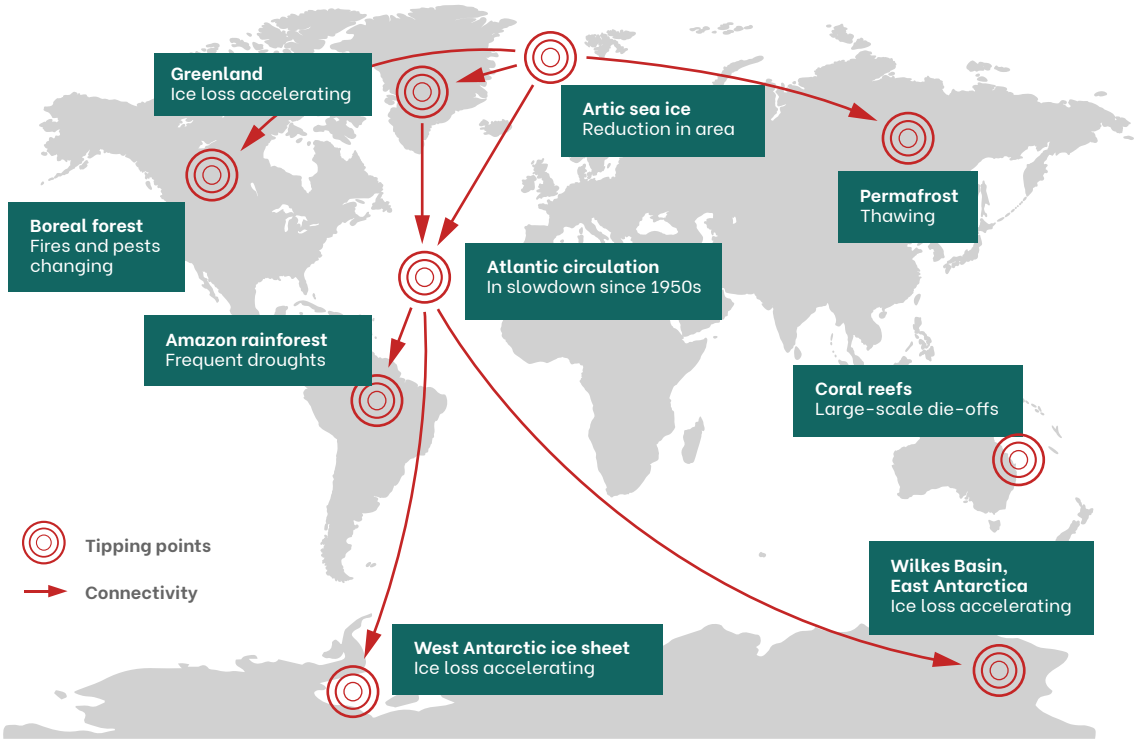
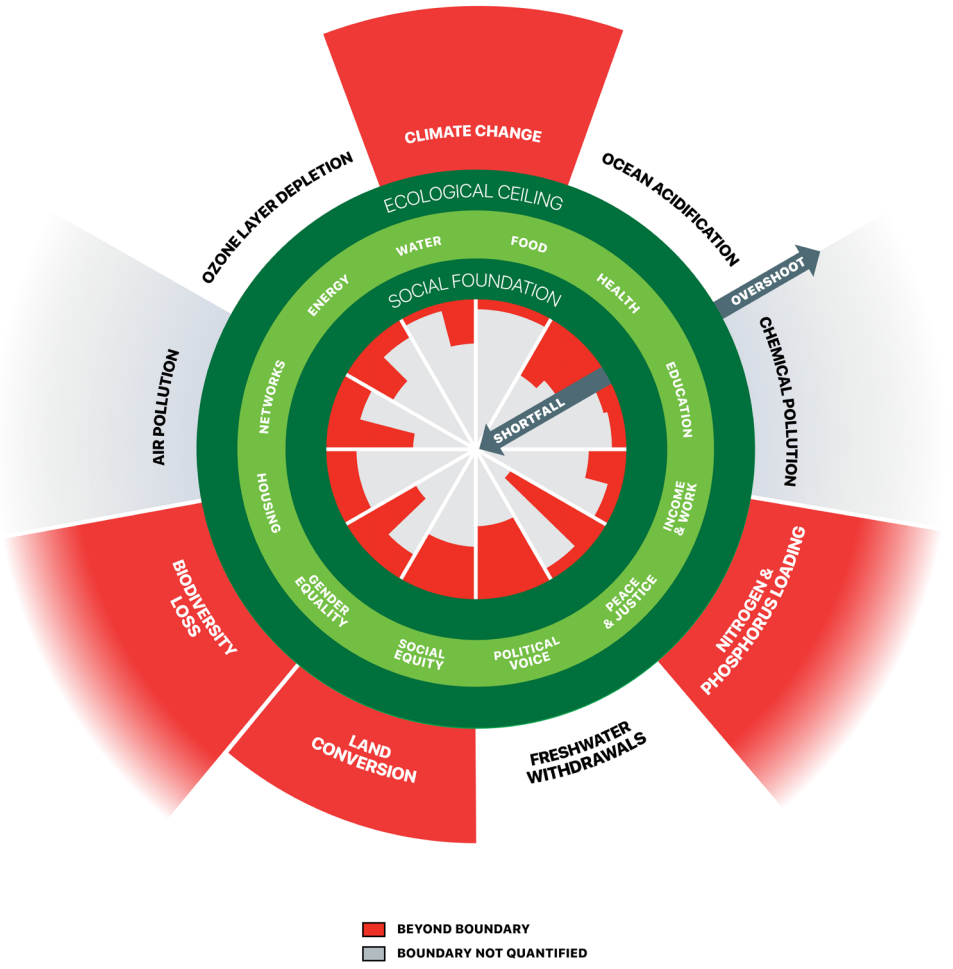


Figure 7: The Planetary Boundaries framework (outer circle) has been combined with a social foundation in the Doughnut economic model, which includes international priorities for human well-being (inner circle).[20]



Following extensive analysis, researchers led by the Stockholm Resilience Centre identified nine key variables that characterise Holocene-like stability (Figure 6). Minimising pressures on these nine interlinked biophysical boundaries helps ensure that the world's societies avoid shifting the planet into a less stable state that is not conducive to human well-being. Applying the precautionary principle and using the latest science to inform their quantification,[5] the planetary boundaries framework defines a *safe operating space* in terms of Earth's biophysical functioning on which human well-being is ultimately dependent at all scales, up to the planetary. More recently, internationally agreed norms for social well-being and equity have been linked to the original planetary boundaries framework, defining the *safe and just* operating space for humanity[20] (Figure 6).

The planetary boundaries framework has shifted the international sustainability discourse to a greater recognition of the larger scale and longer-term systemic consequences of societies' environmental modification, natural resource use and emissions of waste products.

By addressing the framework's nine critical processes and respecting the boundaries, social and economic development can take place without degrading societies' most fundamental life support systems.

As markers of human alteration of Holocene-like conditions, the boundaries are commonly presented in terms of a safe operating space (under the boundary), a zone of uncertainty (beyond the boundary, increasing risk), and beyond the zone of uncertainty (high risk) (Figure 6). To be clear, beyond the safe operating space is a transgression of the boundary with rising risks. The so-called zone of uncertainty refers expressly to computational uncertainty inherent in Earth-system modelling, especially under projected future conditions. The zone of uncertainty does not reflect a lack of scientific consensus about exposure to hazards and risk outside the safe operating space. Beyond the boundaries, risks rise.

Planetary boundaries are sometimes mistaken for tipping points. The framework is set to avoid tipping points, based on what is known about the controls on Earth-system stability. It is better to think of the boundary as similar to a guardrail beside a crumbling cliff edge. Crossing a boundary does not mean falling off a cliff but it certainly raises the risks of doing so.

In addition to global-scale tipping points, Earth-system responses also play out at local and regional scales and alter the overall stability of the system. For example, eutrophication is now a major problem in many rivers, lakes and coastal zones worldwide, with devastating impacts on ecosystem productivity. While there is still no strong consensus that altered water flow has passed a global boundary, many regions face severe shortages and large-scale changes in patterns of atmospheric moisture transport ("moisture recycling") have been observed.[21]

The boundaries are interlinked. Biodiversity loss, land use and altered flows of nitrogen and phosphorus affect the capacity of ecosystems to tolerate perturbations and shocks. For example, as biodiversity is lost it can affect the ability of land ecosystems to store carbon in soils and biomass. This in turn makes it more difficult to stabilise climate change, pushing the planet closer to climate-related tipping points. Steady erosion of biophysical functions affects these abilities to withstand perturbations. Planetary boundaries are set at the point beyond which function erodes and no longer provides the same resilience as before.

1.4 The nine boundaries

1.4.1 Climate change

Global temperature has risen by nearly 1.1°C since the start of the industrial revolution, according to the World Meteorological Organization,[22] primarily as a result of CO_2 emissions from fossil-fuel use. Global average temperature is now outside of the Holocene stability range[2] and the rate of change is accelerating. While uncertainties remain, it is increasingly likely that Earth is crossing tipping points.[11] The world is already experiencing the impacts of climate change. It is affecting the speed at which developing nations are able to develop, exacerbating inequalities even further.[23]

The international community has agreed that CO_2 emissions must decrease, soon and sharply. Meeting the Paris Agreement's goal of stabilising temperature at well below 2°C and aiming for 1.5°C means reaching net-zero emissions by around 2050[24]. A pathway that is consistent with this goal is to halve global fossil-fuel emissions by 2030 (within a decade) and halve again by 2040 and again by 2050 – a pathway called the carbon law.[25] This challenging emissions reduction effort should be accompanied by turning agricultural carbon sources to sinks, protecting existing carbon sinks (forests, wetlands) and creating new carbon sinks, for example through carbon capture and storage technologies.[26]

Recently, several developed economies have committed to reaching net zero by 2050 including New Zealand, France and the United Kingdom. Sweden has committed to reaching this target by 2045, Finland and Norway by 2035.

Policy targets for climate are generally expressed in terms of maximum allowable temperature increase from pre-industrial levels. Implementation requires reductions of society's greenhouse gas emissions. A carbon budget indicates the maximum amount of CO_2 that could be emitted globally in order to stay below a temperature target. Such budgets have been estimated and applied in planetary boundary assessments as we strive for the 2°C and 1.5°C guardrails set forth in the Paris Agreement. However, the safe operating space for climate is defined in terms of two biophysical control variables: changes in radiative forcing and atmospheric CO_2 concentration – both are drivers of global temperature change.

Radiative forcing is the change in energy flux caused by a driver, such as greenhouse gas emissions, and is calculated at the top of the atmosphere. Since pre-industrial times, ever-increasing atmospheric CO_2 concentrations have been the largest contribution to total radiative forcing, tightly coupling these two control variables. The planetary boundary for climate change has been set a) at an atmospheric CO_2 concentration of 350 parts per million (ppm), with increasing risk above 450 ppm, and b) at an increase in radiative forcing is set at 1.0–1.5 W m^{-2} relative to preindustrial levels.[9, 10] As of February 2020, atmospheric CO_2 has reached 414 ppm.[27] According to the IPCC's report Climate Change 2013: The Physical Science Basis, the total anthropogenic radiative forcing for 2011 relative to 1750 is 2.3 W m^{-2} (1.1–3.3 W m^{-2}).[26] Both climate change boundaries have been transgressed.

The IPCC's Special Report Global Warming of 1.5°C (known as SR15)[28] assessed remaining carbon budgets and related uncertainties for staying within 2°C and 1.5°C guardrails. These budgets were assessed in terms of transient climate response to cumulative emissions of CO_2. For example, as Table 1 reports, with a carbon budget of 580 billion tCO_2 from 2018 onward, the likelihood of staying within 1.5°C warming is approximately 50%. The carbon budgets are finite and therefore reduce over time as emissions continue over time. When the climate planetary boundary is set according to a carbon budget, avoiding transgression implies zero emissions once the budget is used – a hard stop. The year of transgression can be estimated assuming e.g. current emission rates continue (Table 1), and various emission reduction pathways can be explored which use the budget at a given annual rate (e.g. current rates, reducing rates) over a given time (e.g. until 2050, 2100).

A so-called Paris goal pathway[29] translates a finite budget consistent with the Paris Agreement, limiting warming to 2°C (>66% likelihood) and to 1.5°C (50% likelihood) by 2100. It is implicit that anthropogenic gross CO_2 emissions peak by 2020, and decline from ~40 $GtCO_2$ yr^{-1} in 2020, to ~24 $GtCO_2$ yr^{-1} by 2030, ~14 $GtCO_2$ yr^{-1} by 2040, and ~5 $GtCO_2$ yr^{-1} by 2050. Even more ambitious is the carbon law pathway to net-zero emissions by 2050, where gross CO_2 emissions exponentially decline, in combination with anthropogenic CO_2 removals and biosphere carbon sinks.[25] Under this pathway (Figure 8) approximately 540 Gt CO_2 is emitted (with continued emissions post-2050). This is a rapid reduction pathway, even so, the associated gross emissions exceed the 1.5°C (67%) carbon budget (420 Gt CO_2) before 2050.

Table 1: Carbon budgets associated with the +2°C and +1.5°C guardrails across three climate response percentiles (in gigatonnes (Gt) CO_2). These carbon budgets were assessed by the IPCC's Special Report (SR15), including discussion of key uncertainties, and reported in SR15 Table 2.2.[28] The response percentiles refer to the likelihood of transient climate response to cumulative carbon emissions, based on the ratio of a unit CO_2 emission and change in global surface temperature. The year of transgression is assessed for this report, estimated assuming "business as usual", where current global emissions continue at a constant rate until the budget is done.

Warming Guardrail	SR15 remaining carbon budget from 2018 [$GtCO_2$] (Year of transgression)		
	33rd percentile	*50th percentile*	*67th percentile*
+1.5°C	**840** (2041)	**580** (2034)	**420** (2029)
+2°C	**2,030** (2074)	**1,5 00** (2059)	**1,140** (2050)

The SR15 carbon budgets are not a revised planetary boundary for climate, rather, they provide parameters for staying within the temperature guardrails, to which emission pathways towards climate stabilisation can be assessed within.

BOUNDARY: Atmospheric CO_2 concentration no higher than 350 ppm

CURRENT (2020)[27]: 414 ppm CO_2

BOUNDARY: Increase in radiative forcing of +1.0–1.5 W m^{-2} relative to preindustrial levels

CURRENT (2011)[26]: +2.3 W m^{-2}

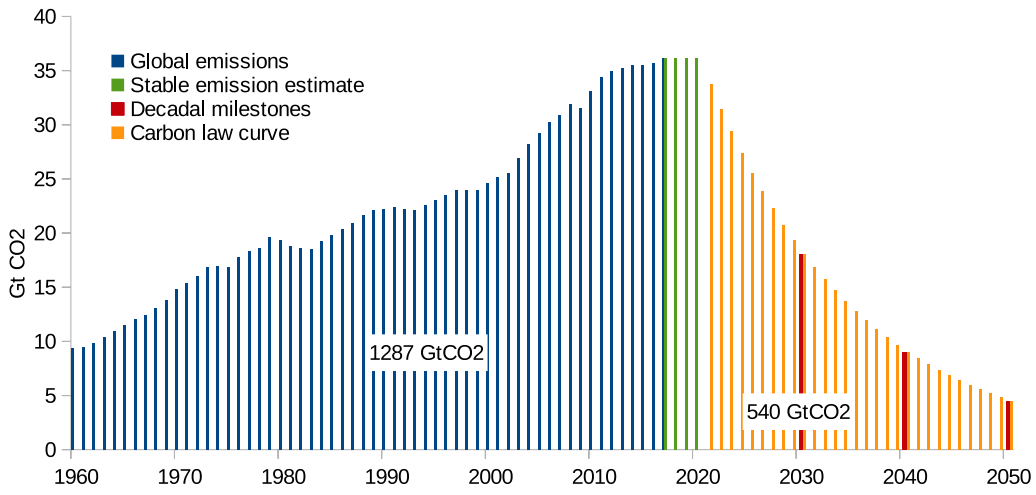
PROPOSED BOUNDARY: Remaining carbon budgets reported in SR15 Table 2.2[28] given annual emission rates and a time horizon

CURRENT (2017)[30]: 36.2 billion tCO_2 yr^{-1}

1.4.2 Biodiversity loss

The safe operating space for biodiversity is defined in terms of the rate at which species go extinct but also the richness of an ecosystem (the value, range, distribution, and relative abundance of the functional traits of the organisms living in the ecosystem).[10] Extinction is an irreversible change in the web of life, and major extinctions are linked with very long-term shifts in Earth-system functioning. Human actions threaten more species with global extinction now than ever before. This has led the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to conclude "around 1 million species already face extinction, many within decades, unless action is taken to reduce the intensity of drivers of biodiversity loss".[30] The IPBES

Figure 8: The carbon law pathway's anthropogenic gross CO_2 emissions. Global gross CO_2 emissions over the historical period 1959–2017 (1287 $GtCO_2$), followed by the carbon law pathway's[24] gross CO_2 emissions component, from 2018 to 2050, whereby current (2017) gross emission levels are halved by 2030, halved again by 2040, and again by 2050. This reduction pathway equates to 540 $GtCO_2$ emitted from 2018–2050.



warns that without major action, the global rate of species extinctions will accelerate. The current extinction rate is already at least tens to hundreds of times higher than the average rate over the past 10 million years.[31]

Ecosystems provide directly beneficial services to people, such as food, fibre and fuel. They also perform many invisible but essential functions, such as the regulation of climate and water cycles, air quality benefits, flood protection, as well as intrinsic benefits contributing to cultural and individual well-being. Losing biodiversity impacts on the resilience of ecosystems and social systems.

Despite considerable conservation efforts over many decades, species declines continue at concerning rates. Conservation efforts can be highly effective but the scale of these efforts cannot keep up with the scale of impacts. Regulations related to conservation, for example through Marine Protected Areas, are often difficult to enforce but when functioning well can support biodiversity goals (e.g.[32, 33]). In 2020, the United Nations Convention on Biological Diversity is likely to adopt new global targets relating to biodiversity.

Combined stressors exacerbate the biodiversity crisis. It is estimated that the world will lose 99% of warm water coral reefs – the most diverse ecosystem in the world's oceans – if global average temperature rises by 2°C. Parts of the Great Barrier Reef may survive if temperatures rise by only 1.5°C.[33]

BOUNDARY: Fewer than 10 extinctions per million species-years

CURRENT: 1. ~1,000 extinctions per million species per year (and rising)[10]

BOUNDARY: Maintain biosphere integrity at 90% or above

CURRENT: 75% (global average)[34]

1.4.3 Land use

Land-system change refers to the transformation of the natural landscape via human processes and modifications. The dominant driver of land-system change is the conversion of natural landscapes for agricultural production. This includes the removal of forests for their resources and/or due to agricultural expansion.

According to the 2019 IPBES global assessment, 75% of Earth's (ice-free) land surface is significantly altered by human activity; 66% of the ocean area is experiencing increasing cumulative impacts, and over 85% of wetland areas have been lost. Since 2000, the rate of forest loss has slowed globally but these changes are distributed unequally with continued high losses, in particular of tropical forests. Between 2010 and 2015, 32 million hectares of primary or recovering forest were destroyed across the highly biodiverse tropics.[31]

The original boundaries assessment proposed a "change in land use" planetary boundary of no more than 15% of global ice-free land surface converted to cropland.[9] Centring the variable on cropland conversion puts importance on biodiversity protection and ecosystem functioning. The updated analysis in 2015 focused on forest cover proposing a "change in land use" planetary boundary such that 75% of original forest cover should remain.[10] Focusing the variable on forest cover puts importance on climate-regulating biogeophysical processes, in addition to biodiversity protection and ecosystem functioning.

The three major forest biomes: tropical, temperate and boreal, play a major role in land surface-climate coupling, where regional land-system changes in these terrestrial biomes can affect climate elsewhere, even globally. Biome-level boundaries are set at forested land as percentage of original (potential) forest.

The **global boundary at 75%** (54–75%) of original forest cover is the average of the three biome-level boundaries.

BOUNDARY: Temperate forest biome: 50% (30–50%); tropical and boreal forest biomes: 85% (60–85%)

CURRENT: 62% of original global forest cover[10]

1.4.4 Freshwater use

Human activity has changed local, continental and global water cycles through damming rivers, irrigation for agriculture, urbanisation, deforestation, drainage of wetlands and climate change. Almost 12% of global annual run-off from rainwater is stored behind reservoirs. Agriculture is the biggest user of freshwater. Worldwide, around 17% of farmland is irrigated.[10] Irrigation in India has been shown to affect large-scale atmospheric moisture fluxes and has been linked to increased rain in the Horn of Africa. Deforestation in the Amazon has been linked to droughts in California and changing rainfall patterns in South America.[10]

The freshwater planetary boundary (revised in 2015[10]) is based on consumptive use of "blue" water, which is water from rivers, lakes, reservoirs and renewable groundwater. This is set at a global usage of 4,000 $km^3\ yr^{-1}$ – a proxy amount that leaves sufficient "green" water for terrestrial and aquatic ecosystem functioning. However, regional and local distinctions remain, and these become important whenever the global guardrail is brought into decision-making at sub-global scales.[35] The actual safe operating space at river-basin scale depends on the specific ecological flow requirements. The update of the planetary boundary in 2015 takes these basin-scale requirements into account. Basin-scale boundaries are set to avoid regime shifts in the functioning of aquatic ecosystems. The analysis indicates where in the world water-cycle perturbations are likely having the greatest effects on Earth-system functioning.

GLOBAL BOUNDARY: 4,000 $km^3\ yr^{-1}$ (4000 – 6000 $km^3\ yr^{-1}$) blue water use

CURRENT (2015)[10]: 2,600 $km^3\ yr^{-1}$

1.4.5 Ozone depletion

The ozone layer protects life on land from harmful radiation from the sun. The planetary boundary for the ozone layer has been set at 275 Dobson Units (DU).[10] The boundary has been transgressed, with levels tipping to 200 DU over Antarctica in the austral springs. By the late 1990s, due to unrestrained growth in ozone-depleting substances, about 10% of the upper ozone layer was depleted.

Adopted in 1987, the Montreal Protocol to phase out ozone-depleting substances is now succeeding. Without the Montreal agreement, levels of ultraviolet radiation reaching the Earth's surface would be approximately 20% higher today than in 1990 at the mid-latitudes. This figure has been predicted to quadruple at mid-latitudes by 2100 if action had failed to stem the rise in harmful chemicals (CFCs).[36]

This is a good example of where a planetary boundary has been transgressed, but how international policy curbed emissions before catastrophe. Since then the ozone layer has increased by 1–3% each decade outside the polar regions. By the 2060s, if controls remain in place, the Antarctic region should be fully recovered. However, in recent years, researchers noticed that ozone-depleting emissions in some places have been rising even as emissions fell globally. In 2019, they identified the source to factories in China that were ignoring legislation on banned chemicals.

The ban on harmful CFCs led to industry switching to gases less damaging to the ozone layer (HFCs) but more damaging to the climate. Some gases have a warming potential several thousand times that of CO_2. The Montreal Protocol has been amended to reduce the use of these chemicals by 80% by 2047 and if successful will also have an important role in helping stabilise Earth's climate.

BOUNDARY: No lower than 276 DU ozone (latitude-dependent)

CURRENT: 283 DU and improving[10]

1.4.6 Ocean acidification

The ocean absorbs approximately one-quarter of the CO_2 emitted by human activity. CO_2 is a weak acid, so as a result the pH of the world's ocean is falling. It has dropped 26% since the start of the Industrial Revolution. The rate of change is unprecedented in human history and likely unprecedented in 300 million years.[37]

Ocean acidification has now been linked to several mass extinctions including the demise of non-avian dinosaurs.[38]

Current levels of ocean acidification are already affecting coral reefs and creatures with shells, including some species of plankton at the base of the marine food chain.

The ocean acidification boundary is defined in terms of the aragonite saturation state, a measure of how much a particular form of calcium carbonate dissolves in the ocean.[10] It is a measure that is more directly linked to the effects on marine organisms and the carbon cycle than ocean pH. The marine carbonate system is highly variable around the world and through the seasons, making it difficult to obtain a global picture of acidification, but the boundary has not yet been transgressed. Reducing CO_2 emissions to the atmosphere will directly reduce the risk of transgressing the ocean acidification planetary boundary.

Ecological evidence and scientific understanding of impacts are growing. By 2100, just 25% of existing cold-water coral around New Zealand will be able to sustain their growth with rising ocean acidification, according to New Zealand's National Institute for Water and Atmospheric Research (NIWA).[39] Ocean acidification is also predicted to impact aquaculture, for example, mussel farming. Fish farms on the Pacific Coast of the United States are already affected.

BOUNDARY: 80% of pre-industrial ocean aragonite saturation

CURRENT: ~84% of pre-industrial ocean aragonite saturation, and falling[10]

1.4.7 Biogeochemical cycles (nitrogen and phosphorus flows)

Human activities are altering several of Earth's critical biogeochemical cycles. The water and carbon cycles are dealt with in the water and climate boundaries. However, the cycles of phosphorus and nitrogen, both essential nutrient elements, have also been profoundly altered, largely through the use of industrial fertilisers used in agriculture. Viewed in quantitative terms, the nitrogen cycle has arguably been altered more than the carbon cycle (although all these cycles interact in Earth-system functioning).[10] These changes in nutrient flows have implications at local levels, as water quality of lakes and rivers decreases and soil quality declines. Beyond the national level, coastal areas and seas are also affected through eutrophication and the expansion of dead zones. These changing cycles have implications up to the global level, for example, affecting climate patterns: one by-product of industrial agriculture is nitrous oxide, a powerful greenhouse gas. They are also implicated in large-scale ecosystem change, on land and in the marine environment.

Nitrogen and phosphorus have been essential to the success of the agricultural revolution of the 21st century. They have allowed farmers to feed billions more people. However,

their use and impacts are unevenly spread throughout the world. Africa does not have enough nutrient resources while Europe, North America and parts of Asia have too much.[10] A distinction should be made between biogeochemical analysis based on applications (quantities of nutrients applied on land) and emissions (quantity of nutrient losses to water bodies and air).[40]

The nitrogen boundary is based on eutrophication of aquatic ecosystems from industrial and intentional biological nitrogen fixation using the most stringent water quality criterion.[10] Given that the addition of phosphorus to regional watersheds is almost entirely from fertilizers, the regional-level boundary applies primarily to the world's croplands. Just a few agricultural regions are the main contributors to transgression of the phosphorus boundary due to very high phosphorus application rates. The boundaries refer to nitrogen and phosphorus application rates. More recently, some analyses have included loss of nitrogen and phosphorus from agriculture.[40] The boundary for nitrogen loss is approximately half (46%) the application boundary. In this analysis we primarily focus on application.

PHOSPHORUS (P) BOUNDARY: No more than 6.2 million tonnes (Mt) P applied to land per year

CURRENT (2015)[41]: ~9.7 Mt yr^{-1}

NITROGEN (N) BOUNDARY: No more than 62 million tonnes (Mt) N applied to land per year

CURRENT (2015)[41]: ~48.5 Mt yr^{-1}

1.4.8 Atmospheric aerosols

Aerosols – small particles in the air – are detrimental to human health and contribute to over 7 million deaths worldwide every year.[10] They also affect the functioning of the Earth system by influencing the amount of incoming radiation hitting the planet but also in complex ways influencing weather patterns and formation of clouds. Some aerosols caused by pollution from transport and industry cause warming, while others have a strong cooling effect.

While there is no doubt that human activities have profoundly altered the composition and distribution of atmospheric aerosols, especially since the Industrial Revolution, it is much less clear how these qualitative Earth-system changes relate to the absolute amounts of aerosols. For this reason, the aerosol boundary has not been fully quantified and a first estimate is expected in 2020.[10]

PLANETARY BOUNDARY – UNQUANTIFIED: Although Aerosol Optical Depth (AOD) is measured globally

REGIONAL BOUNDARY: For the South Asian case study, a total anthropogenic AOD of 0.25 (uncertainty range 0.25–0.50); fraction of absorbing (warming) aerosol less than 10% of total AOD

CURRENT VALUE: 0.30 AOD over South Asian region, breaching the regional boundary[10]

1.4.9 Novel entities

Synthetic substances – and even novel life-forms – can radically alter Earth's biological and physical dynamics, bringing entirely new systemic risks to human societies. More than 100,000 substances are used in the global economy. This list grows longer if plastic polymers that degrade into microplastics are included.[10]

In the planetary boundaries framework, novel entities refers to plastics, nuclear material, genetically modified organisms, new chemicals, nanoparticles and even artificial intelligence.[10] Question marks remain over the behaviour of these substances in the environment. How will they affect life and geochemical cycles? Will they break down into more harmful substances? How do they interact? The CFC family of chemicals was chosen for use in refrigerators because of its relative stability. However, in the upper atmosphere they were not stable and widespread usage resulted in a hole in the ozone layer.

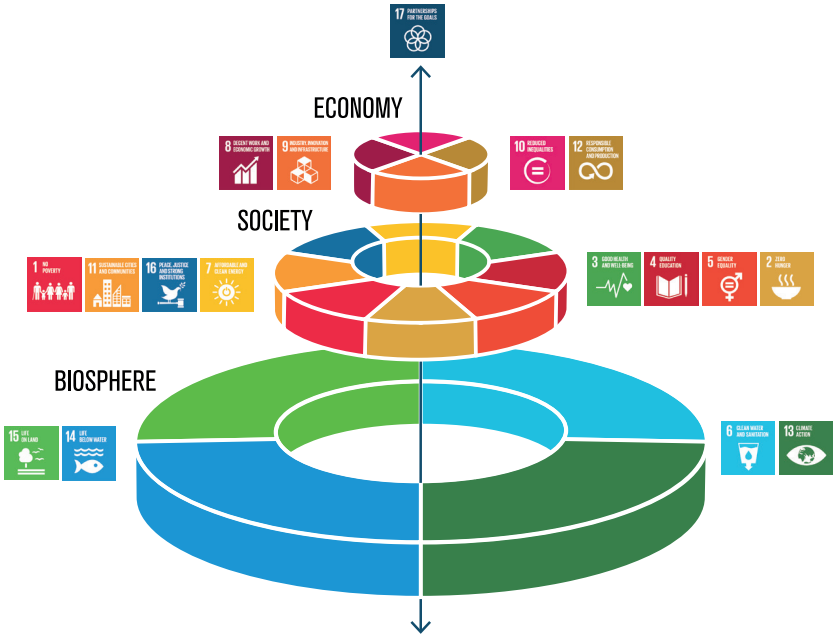
Due to considerable uncertainties and fundamental complexities, this boundary has not been quantified, but cross-disciplinary scientific analysis is shedding light on critical threats. The planetary boundaries framework suggests applying three conditions to be fulfilled for a novel entity to pose a threat to the Earth system: (i) it has the capacity to have a disruptive effect on a vital Earth-system process; (ii) the disruptive effect is not discovered until it is a problem at the global scale; and (iii) the effect is not readily reversible.[42]

BOUNDARY: No single quantification; strong precautionary and preventive measures recommended.

1.5 A paradigm shift towards planetary stewardship?

The Anthropocene as described above, has led to a significantly improved understanding of Earth as a system, how humans are changing it and its potential future trajectories. It marks a shift towards stronger scientific integration across scales, regions and disciplines, for example with respect to understanding environmental and social tipping points. This knowledge is paving the way for a political and cultural paradigm shift in relation to how national economies and the global economy influence the planet and vice versa. In this new paradigm, a healthy economy promotes human well-being and planetary stewardship. And vice versa: well-functioning ecosystems and a resilient planet are essential for a functioning society and thriving economy (Figure 9).

Figure 9: Society and the biosphere are often incorrectly perceived as beyond or outside of the economy – as externalities. This figure, based on arrangement of the Sustainable Development Goals, more correctly positions the economy as within society, which in turn is within the biosphere. Image: Stockholm Resilience Centre



This dependence of humanity on the local-to-global environment is recognised by a growing number of actors, for example companies, cities and national governments, who pose the question to science, how can they meet their global environmental responsibility? In response to this question, researchers at the Potsdam Institute for Climate Impact Research, the Mercator Research Institute on Global Commons and Climate Change and the Stockholm Resilience Centre work in close collaboration with these actors to support translation and operationalisation to mainstream the planetary boundaries for these respective contexts. This co-development of relevant and actionable knowledge can add value by aligning local targets and national future pathways with new considerations relating to planetary stewardship, including intergenerational equity. Ultimately, research in the last two decades relating to the Anthropocene points to a new worldview: our global commons is a stable, resilient planet and this is now at risk.[43]

1.5.1 Translating planetary boundaries to national-scale action

The planetary boundaries provide a global-scale and long-term biophysically defined systemic perspective on acceptable environmental change, providing a complement to the diverse approaches for local-scale sustainability and environmental impact assessment. Planetary boundaries are not motivated just by direct regional or local impacts (e.g., water abstraction leading to inadequate flows; excess nutrient release leading to eutrophication), but by systemic large-scale and long-term impacts: alterations to the dynamic interactions and feedbacks between the climate, biosphere, land, oceans and atmosphere that together make up Earth resilience.

Global boundaries on Earth-critical environmental impacts clearly have implications for societies' consumption and production processes, resource use and emissions of waste products. They also point toward issues of internationally coordinated management of the natural environment, burden sharing and fairness in attributing responsibility for staying within the planetary boundaries.[44] Scientific evidence for environmental boundaries across scales and the ability to stay within them over longer timescales is important to ensure intergenerational sustainable use of resources and environmental conditions that support human well-being.

"Downscaling" is the process of translating globally defined Earth-system boundaries into locally or nationally actionable targets, by allocating fair shares of the global safe operating space to entities such as cities, countries or regions. It can thus increase the policy impact of the planetary boundaries framework. Several research groups have assessed the scope for translating planetary boundaries to sub-global and sectoral decision-making levels (Table 2). These assessments include studies commissioned by national governments, including Sweden, Switzerland, South Africa and Germany.

Table 2: National and sectoral studies of planetary boundaries (* = policy-oriented applications)

Country/sector	Approach	References
Sweden*	Production/consumption comparison	Swedish Environmental Protection Agency (Nykvist et al. 2013)[45]
Switzerland*	Production/consumption comparison, footprint-based target setting	Frischknecht et al. 2016;[46] Dao et al. 2015, 2018[47,48]
Germany*	Footprinting, political implementation viability	German Environment Agency (H. Hoff and B. Keppner 2017)[49]
Netherlands*	Production/consumption comparison	Netherlands Environmental Assessment Agency (PBL) (Lucas and Wilting 2018)[50]
EU*	Production/consumption comparison	EU 7th Environment Action Programme ("Living well, within limits of our planet");[51] ESDN/Pisano and Berger 2013 (8 countries);[52] EEA/Häyhä et al. 2018;[53] EEA/FOEN 2020[40]
Finland*	Production/consumption comparison	SYKE (Furman et al. 2018)[54]
South Africa	Expert elicitation	Cole et al. 2014[55]
Spain	Input-output analysis for footprints	Fanning and O'Neill 2016[56]
Canada	Input-output analysis for footprints	Fanning and O'Neill 2016[56]
China/regional (ecosystem services)	Historic flows correlation, tipping point identification	Dearing et al. 2014[57]
Colombia/Orinoco Basin	Ecosystem accounting	Vargas-Gonzalez 2018[58]
151 countries (land, water, climate and biogeochem)	Per capita consumption-based	O'Neill et al. 2018[59]
EU, US, China and India	Consumption-based; different allocation approaches	Lucas et al. 2020[60]
28 countries (land, water, climate)	Footprinting	Fang et al. 2015[61]
Urban	Context-based target setting	Hoornweg et al. 2016[62]
Life-cycle impacts	"Absolute" LCA (causality) methodology	Bjørn et al. 2016[63]
Investments, finance	Economic input-output-LCA	Butz et al. 2018[64]
Agriculture/food security (Finland, Ethiopia)	Time-based cumulative flow, rights-based	Kahiluoto et al. 2015[65]

1.5.2 What boundaries can be translated for New Zealand?

This report translates five of the nine planetary boundaries to the New Zealand context:

1. Climate change
2. Biodiversity loss
3. Biogeochemical cycles (nitrogen and phosphorus flows)
4. Freshwater use
5. Land use

These five planetary boundaries are especially well-suited to a national translation effort. The key drivers of boundary transgression, the potential options for mitigation and the scientific analysis of alternative pathways are sufficiently well characterised for translation into national-level structures, policies and management strategies.

Also, for these five boundaries, there are large-scale (if not yet global) scientific assessments that give a coherent evidence base to support national target-setting, as well as broad international agreement on the need for concerted action.

The remaining four boundaries will not be addressed in detail in this report:

- Ocean acidification is a direct consequence of CO_2 emissions, therefore management of greenhouse gas emissions to mitigate climate change will also help reduce the impact of ocean acidification.
- Ozone depletion, as discussed earlier, is now on a path to recovery. The Montreal Protocol has successfully led to a decline in emissions of ozone-depleting chemicals to such an extent that the ozone boundary, once transgressed, is now within a global safe operating space. However, some risks clearly still apply to New Zealand, as its geographic location places it at direct risk from an expanding ozone hole.
- Aerosol loading has complex influences on the planet. Given no quantitative planetary boundary has been defined, it is not possible to translate this planetary boundary to New Zealand.
- A quantitative boundary for novel entities has not been established due to the sheer number of entities in the environment and their complex interactions.

1.6 New Zealand context

This is the first translation of the planetary boundaries framework to an island nation. The analysis quantifies New Zealand's territorial footprint related to the boundaries assessed and the country's consumption footprint from imported goods consumed in New Zealand.

Island nations, particularly New Zealand, have interesting idiosyncrasies compared with, for example, tightly physically, economically and biologically connected European countries. New Zealand has a unique and rich biodiversity – biodiversity strengthens the resilience of the Earth system. New Zealand has a long history of environmental stewardship but also land-use change, particularly deforestation. It has abundant freshwater, but water quality is an issue. And unlike some other advanced economies, agriculture products are major export commodities – New Zealand's lands feed many more people than those living on the islands. Here we summarise the New Zealand context specifically related to assessed planetary boundaries.

Agriculture

Agriculture is one of New Zealand's primary sectors. Temperate climatic conditions and abundant natural resources allow for a wide range of foods to be produced and harvested from soils and seas. The scale, specialisation and intensification of the New Zealand agricultural sector have, however, led to several environmental challenges.

Agriculture contributes almost half of New Zealand's total greenhouse gas emissions, mainly methane and nitrous oxide emissions resulting from livestock production.[66] Growth in livestock production is reflected in rising agricultural emissions – a 12% increase from 1990–2016.[66]

Over 40% of New Zealand's total land area is occupied by agriculture (both cropland and pasture), including dairy (10%), livestock (32%) and horticultural production (1%).[67] Recent years have seen a slight decline in total land use for agriculture, although specific farming activities have shown different trends. For example, dairy farming in 2016 occupied 42% more land area than in 2002, while sheep and beef farming occupied 20% less land in the same time period.[67]

Dairy farming in particular has raised a number of environmental concerns. With the intensification of dairy farming in New Zealand came increased inputs, such as feed and fertilisers.[68] Production of feed is associated with its own environmental impacts, for example production of palm kernel (imported to New Zealand) can be associated with deforestation and the resultant loss of biodiversity and greenhouse gas emissions elsewhere.

Consumption and production

New Zealand's highest earning export commodities are dairy and forest products, with major trade partners in China, Australia, the United States and the EU.[69] It is therefore likely that a high proportion of domestic land use and agricultural impacts are allocated to consumers outside of New Zealand. This contrasts with many other advanced economies where environmental pressures tend to increase when accounting for consumption impacts rather than production-based accounts.[70]

On the flip side, New Zealand imports a large volume of manufactured goods, in particular vehicle parts and mechanical machinery.[70] Since these goods have energy-intensive supply chains, New Zealand is likely to remain consistent with other wealthy countries for climate impacts: allocated environmental pressures will increase from a consumption-based perspective.

Climate

Recently, several developed economies have committed to reach net zero by 2050 including New Zealand, France and the United Kingdom. New Zealand's territorial CO_2 emissions were 35 Mt CO_2 in 2018, approximately 7.4 tCO_2 per person in 2018.[71] Emissions peaked in 2008, declined slightly and have remained relatively stable since 2010 according to the Global Carbon Project.[30] New Zealand is ranked 46th in the world of highest CO_2 emitters. This is significantly below high emitters like Australia but its emissions are substantially higher than the global average per capita of 5tCO_2 per person. New Zealand's largest source of CO_2 emissions come from energy production and transport. However, greenhouse gas emissions more broadly increased 19.6% from 1990–2016. In 2016, gross greenhouse gas emissions were mainly made up of CO_2 (43.8%), methane (42.8%) and nitrous oxide (11.6%).[66]

Land use (forestry)

Prior to human settlement, New Zealand was almost entirely forested, at 80–85% of its land area, with the exception of high mountainous regions and active volcanoes.[72] By preindustrial times, deforestation had occurred from both Māori and European settlers, with an estimated reduction to 53% of total land area in 1840.[72] New Zealand's current forest cover is 39% (10.2 million ha) of its land area,[66] however, of this, just 30% is considered indigenous forest.[67]

Biodiversity

Deforestation, agriculture and marine harvesting negatively affect biodiversity. According to New Zealand's Threat Classification System (NZTCS), out of about 11,000 native species monitored about 4,000 are at risk or threatened with extinction. Of New Zealand's marine species, 90% of seabirds, 80% of shorebirds, and 26% of native marine mammals are either threatened with or at risk of extinction.[66] For example, the use of trawling or dredging in New Zealand waters can damage marine ecosystems and reduce the biodiversity of species living in those habitats. In inland waters, pollution from agriculture and soil erosion – often accelerated by farming practices – has reduced biodiversity in some regions.[73] On land, agricultural expansion and deforestation have led to the loss of natural habitats, fuelling the decline of native species.[67]

Nitrogen and phosphorus use

According to the OECD Environmental Performance Review,[74] nitrogen leaching into soils from agriculture increased by 29% between 1990–2012, and in rivers nitrogen levels increased 12%. Nitrogen pollution hotspots include Canterbury, Otago, Southland, Waikato, Taranaki, Manawatu-Wanganui and Hawke's Bay.

The OECD Environmental Performance Review concludes that between 1998–2009, New Zealand's nitrogen balance worsened more than in any other OECD member country, "primarily due to expansion and intensification of farming". The authors say, "The national nitrogen surplus increased at a similar annual rate to that of the national dairy cattle herd".

Phosphorus shows similar trends in lowland farming catchment areas, though efforts to reduce impacts have shown some signs of success. The Ministry for the Environment reports that progress to reduce phosphorus leaching has resulted in concentrations reducing at median rates >1.5% per year between 2004–2013.[74]

Freshwater

New Zealand has "a natural abundance of freshwater and low water stress at the national level".[74] Water allocated for agriculture and other uses makes up just 5% of renewable freshwater resources. But this national picture masks regional variations. About 75% of consumptive freshwater use is for irrigation of pastoral and arable land. Of this, 78% of the irrigation is for agriculture on the South Island regions of Canterbury and Otago where "water availability would otherwise be a limiting factor for intensive land use". The OECD Environmental Performance Review concludes that some parts of the country are approaching allocation limits or have already surpassed them. Beyond water extraction, water quality is viewed as a significant concern in New Zealand.

New Zealand context for the boundaries not quantified in this analysis (ozone, ocean acidification, aerosols and novel entities)

New Zealand's population has the highest rates of skin cancer in the world, and high ultraviolet radiation and low ozone levels are important contributing factors. Without the Montreal Protocol to curb ozone-depleting substances, this rate would likely have increased.[75-77] However, some risks clearly still apply to New Zealand, as its geographic location places it at direct risk from an expanding ozone hole.

By 2100, just 25% of existing cold-water coral around New Zealand will be able to withstand rising ocean acidification. Ocean acidification is also predicted to impact aquaculture, for example, mussel farming.

Generally, air quality is good by international standards and has improved due to standards relating to emissions and efficiency. However, emissions of some major air pollutants (nitrogen and sulphur oxides, and non-methane volatile organic compounds) rose between 2000–2014 with increasing road transport, industrial production and power generation.

New Zealand policy related to novel entities includes restrictions on marine pollution and bans on plastic microbeads in cosmetics and cleaning products, and single-use plastic bags and persistent organic pollutants.

References

1. M. Willeit, A. Ganopolski, R. Calov, V. Brovkin, Mid-Pleistocene transition in glacial cycles explained by declining CO_2 and regolith removal. *Science Advances*. 5, eaav7337 (2019).
2. S. A. Marcott, J. D. Shakun, P. U. Clark, A. C. Mix, A Reconstruction of Regional and Global Temperature for the Past 11,300 Years. *Science*. 339, 1198–1201 (2013).
3. P. H. Kavanagh, B. Vilela, H. J. Haynie, T. Tuff et al., Hindcasting global population densities reveals forces enabling the origin of agriculture. *Nature Human Behaviour*. 2, 478–484 (2018).
4. Ganopolski, R. Winkelmann, H. J. Schellnhuber, Critical insolation–CO 2 relation for diagnosing past and future glacial inception. *Nature*. 529, 200–203 (2016).
5. W. Steffen, W. Broadgate, L. Deutsch, O. Gaffney, C. Ludwig, The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review*. 2, 81–98 (2015).
6. D. Griggs, M. Stafford-Smith, O. Gaffney et al., Sustainable development goals for people and planet. *Nature*. 495, 305–307 (2013).
7. J. D. Sachs, G. Schmidt-Traub, M. Mazzucato et al., Six Transformations to achieve the Sustainable Development Goals. *Nature Sustainability*. 2, 805–814 (2019).
8. Agenda 2030 (2015) United Nations Official Document. Paragraph 55, available at www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.
9. J. Rockström, W. Steffen, K. Noone et al., A safe operating space for humanity. *Nature*. 461, 472–475 (2009).
10. W. Steffen, K. Richardson, J. Rockström et al., Planetary boundaries: Guiding human development on a changing planet. *Science*. 347 (2015), doi:10.1126/science.1259855.
11. T. M. Lenton, H. Held, E. Kriegler et al., Tipping elements in the Earth's climate system. *PNAS*. 105, 1786–1793 (2008).
12. T. M. Lenton, J. Rockström, O. Gaffney et al., Climate tipping points — too risky to bet against. *Nature*. 575, 592–595 (2019).
13. IPCC, IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (H.-O. Pörtner et al. (Eds.)), (2019). Available at www.ipcc.ch/srocc/download-report/.
14. Dutton, A. E. Carlson, A. J. Long et al., Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science*. 349 (2015), doi:10.1126/science.aaa4019.
15. C. A. Nobre, G. Sampaio, L. S. Borma et al., Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *PNAS*. 113, 10759–10768 (2016).
16. T. E. Lovejoy, C. Nobre, Amazon Tipping Point. *Science Advances*. 4, eaat2340 (2018).
17. W. Hubau et al. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*. 579, 80–87 (2020).
18. J. C. Rocha, G. Peterson, Ö. Bodin, S. Levin, Cascading regime shifts within and across scales. *Science*. 362, 1379–1383 (2018).
19. W. Steffen, J. Rockström, K. Richardson, T. M. Lenton et al., Trajectories of the Earth System in the Anthropocene. *PNAS*. 115, 8252–8259 (2018).
20. K. Raworth, A Doughnut for the Anthropocene: humanity's compass in the 21st century. *The Lancet Planetary Health*. 1, e48–e49 (2017).
21. P. W. Keys et al., Analyzing precipitation sheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences* .9, 733–746 (2012).
22. World Meteorological Organization, WMO confirms 2019 as second hottest year on record (2020). Available at https://public.wmo.int/en/media/press-release/wmo-confirms-2019-second-hottest-year-record.
23. N. S. Diffenbaugh, M. Burke, Global warming has increased global economic inequality. *PNAS USA*. 201816020 (2019).
24. C.-F. Schleussner et al., Differential Climate Impacts for Policy-Relevant Limits to Global Warming: The Case of 1.5 degC and 2 degC. *Earth System Dynamics*. 7(2), 327–51 (2016). Available at www.earth-syst-dynam.net
25. J. Rockström, O. Gaffney, J. Rogelj et al., A roadmap for rapid decarbonization. *Science*. 355, 1269–1271 (2017).
26. IPCC, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (T. F. Stocker et al. (Eds.)) (2013).
27. The National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division, Trends in atmospheric carbon dioxide (2019). Available at www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html.
28. IPCC, IPCC Special Report on Global warming of 1.5°C. (V. Masson-Delmotte et al. (eds.), (2018). Available at www.ipcc.ch/sr15/.
29. J. Rogelj, G. Luderer, R. Pietycker et al., Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*. 5, 519-527 (2015).
30. Global Carbon Atlas, New Zealand emissions. Available at www.globalcarbonatlas.org/en/content/welcome-carbon-atlas

31. S. Díaz, J. Settele, E. Brondízio et al., Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). Available at https://uwe-repository.worktribe.com/output/1493508.

32. K. A. Kaplan, G. N. Ahmadia, H. Fox et al., Linking ecological condition to enforcement of marine protected area regulations in the greater Caribbean region. *Marine Policy*. 62, 186–195 (2015).

33. S. Murray, T. T. Hee, A rising tide: California's ongoing commitment to monitoring, managing and enforcing its marine protected areas. *Ocean & Coastal Management*. 182, 104920 (2019).

34. K. Sanchez-Ortiz, R. E. Gonzalez, A. De Palma et al., Land-use and related pressures have reduced biotic integrity more on islands than on mainlands. *bioRxiv* (pre-print). Available at https://doi.org/10.1101/576546.

35. D. Gerten, H. Hoff, J. Rockström et al., Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Current Opinion in Environmental Sustainability. 5(6), 551–558 (2013).

36. R. McKenzie, G. Bernhard, B. Liley et al., Success of Montreal Protocol Demonstrated by Comparing High-Quality UV Measurements with "World Avoided" Calculations from Two Chemistry-Climate Models. *Scientific Reports*. 9, 1–13 (2019)

37. B. Hönisch, A. Ridgwell, D. N. Schmidt et al., The Geological Record of Ocean Acidification. *Science*. 335, 1058–1063 (2012).

38. M. J. Henehan, A. Ridgwell, E. Thomas et al., Rapid ocean acidification and protracted Earth system recovery followed the end-Cretaceous Chicxulub impact. *PNAS*. 116, 22500–22504 (2019).

39. NIWA, Investigating ocean acidification, (2016). Available at https://niwa.co.nz/news/investigating-ocean-acidification (accessed 27 April 2020).

40. EEA, FOEN, Is Europe living within the limits of our planet? An assessment of Europe's environmental footprints in relation to planetary boundaries. Joint EEA/FOEN Report, European Environment Agency (2020).

41. FAO, Food and Agriculture Organisation of the United Nations: FAOSTAT Database Online (2019). Available at http://faostat.fao.org/.

42. L. M. Persson, M. Breitholtz, I. T. Cousins et al., Confronting unknown planetary boundary threats from chemical pollution. *Environ. Sci. Technol.* 47, 12619–12622 (2013).

43. N. Nakicenovic, J. Rockström, O. Gaffney, C. Zimm, Global Commons in the Anthropocene: World Development on a Stable and Resilient Planet (2016). Available at http://pure.iiasa.ac.at/id/eprint/14003/.

44. T. Häyhä, P. L. Lucas, D. P. van Vuuren, S. E. Cornell, H. Hoff, From planetary boundaries to national fair shares of the global safe operating space – How can the scales be bridged? *Global Environmental Change*. 40, 60–72 (2016).

45. B. Nykvist et al., National Environmental Performance on Planetary Boundaries. Swedish Environmental Protection Agency Report 6576, Stockholm (2013).

46. R. Frischknecht, P. Stolz, L. Tschümperlin, National environmental footprints and planetary boundaries: from methodology to policy implementation. *International Journal of Life Cycle Assessment*. 21, 601–605 (2016).

47. H. Dao, D. Friot, P. Peduzzi et al., Environmental limits and Swiss footprints based on planetary boundaries. UNEP/GRID-Geneva & University of Geneva, commissioned by the Swiss Federal Office for the Environment (FOEN) (2015).

48. H. Dao, P. Peduzzi, D. Friot, National environmental limits and footprints based on the Planetary Boundaries framework: The case of Switzerland. Global Environmental Change. 52 49–57 (2018). Available at https://doi.org/10.1016/j.gloenvcha.2018.06.005.

49. H. Hoff and B. Keppner, Planetary Boundaries: current status, trends, risks, criticality – what do we know, and what do we need to know?, German Environment Agency Report No. UBA FB 00 (2017)

50. P. Lucas, H. Wilting, Using planetary boundaries to support national implementation of environment-related Sustainable Development Goals. Report No 2748, Netherlands Environmental Assessment Agency (2018).

51. European Commission, Living well, within the limits of our planet: 7th EAP – the new general Union Environment Action Programme to 2020, European Commission, Brussels, Belgium (2013).

52. U. Pisano, G. Berger, Planetary Boundaries for SD: From an international perspective to national applications. October 2013, ESDN Quarterly Report N°30 (European Sustainable Development Network) (2013).

53. T. Häyhä, S. Cornell, H. Hoff, P. Lucas, D. van Vuuren, Operationalizing the concept of a safe operating space at the EU level – first steps and explorations. Stockholm Resilience Centre, Stockholm, Sweden (2018).

54. E. Furman, T. Häyhä, T. Hirvilammi, A future the planet can accommodate. SYKE Policy Brief – Finnish Environment Institute (2018). Available at http://hdl.handle.net/10138/235418.

55. M. J. Cole, R. M. Bailey, M. G. New, Tracking sustainable development with a national barometer for South Africa using a downscaled 'safe and just space' framework. PNAS *USA*. 111, E4399–408 (2014).

56. A. L. Fanning, D. W. O'Neill, Tracking resource use relative to planetary boundaries in a steady-state framework: a case study of Canada and Spain. *Ecological Indicators*. 69, 836–49 (2016).

57. J. Dearing et al., Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*. 28, 227–238 (2014).

58. M. Vargas-Gonzalez, Integrating the Concept of Planetary Boundaries into Decision Making Processes. In: *Designing Sustainable Technologies, Products and Policies*, Springer, 407–412 (2018).

59. D. W. O'Neill, A. L. Fanning, W. F. Lamb, J. K. Steinberger, A good life for all within planetary boundaries. *Nature Sustainability*. 1, 88–95 (2018).

60. P. Lucas, C. Wilting, A .Hof, et al., Allocating planetary boundaries to large economies: Distributional consequences of alternative perspectives on distributive fairness. *Global Environmental Change.* 60 (2020).

61. K. Fang, R. Heijungs, Z. Duan, G.R. de Snoot, The environmental sustainability of nations: Benchmarking the carbon, water and land footprints against allocated planetary boundaries. *Sustainability*. 7(8), 11285–11305 (2015).

62. D. Hoornweg, M. Hosseini, C. Kennedy, A. Behdadi, An urban approach to planetary boundaries. *Ambio*. 45(5), 567–580 (2016).

63. A. Bjørn, M. Margni, P.O. Roy et al., A proposal to measure absolute environmental sustainability in life cycle assessment. *Ecological Indicators*. 63, 1–13 (2016).

64. C. Butz, J. Liechti, J. Bodin, S. E. Cornell, Towards defining an environmental investment universe within planetary boundaries. *Sustainability Science*. 13(4), 1031–1044 (2018).

65. H. Kahiluoto et al. Local and social facets of planetary boundaries: right to nutrients. *Environmental Research Letters*. 10, 104013 (2015).

66. Ministry for the Environment, Stats NZ, New Zealand's Environmental Reporting Series: Environment Aotearoa 2019. Wellington (2019). Available at: www.mfe.govt.nz

67. Ministry for the Environment, Stats NZ, New Zealand's Environmental Reporting Series: Our land 2018 (2018).

68. R. McDowell, R. Monaghan, W. Dougherty et al., Balancing water-quality threats from nutrients and production in Australian and New Zealand dairy farms under low profit margins. *Animal Production Science 2017*. 57(7), 1419-30.

69. G. P. Peters, J. C. Minx, C. L. Weber, O. Edenhofer, Growth in emission transfers via international trade from 1990 to 2008. *PNAS*. U. S. A. 108, 8903–8 (2011).

70. Goods and services trade by country: Year ended March 2018, Available at www.stats.govt.nz/information-releases/goods-and-services-trade-by-country-year-ended-march-2018.

71. New Zealand Ministry for the Environment, New Zealand's Greenhouse Gas Inventory. Available at www.mfe.govt.nz/climate-change/state-of-our-atmosphere-and-climate/new-zealands-greenhouse-gas-inventory (accessed April 2020).

72. Ministry for the Environment, Stats NZ, New Zealand's Environmental Reporting Series: Predicted pre-human vegetation (2015).

73. J. Ramezani, A. Akbaripasand, G. Closs, C. Matthaei. In-stream water quality, invertebrate and fish community health across a gradient of dairy farming prevalence in a New Zealand river catchment. *Limnologica*. 61, 14–28 (2016

74. OECD Environmental Performance Reviews: New Zealand (2017). Available at https://www.oecd.org/newzealand/oecd-environmental-performance-reviews-new-zealand-2017-9789264268203-en.htm

75. World Meteorological Organization (WMO), GORMP, 58. Scientific Assessment of Ozone Depletion: 2018 (WMO, Geneva, 2018), technical document.

76. R. McKenzie, G. Bernhard, B. Liley et al., Success of Montreal Protocol Demonstrated by Comparing High-Quality UV Measurements with "World Avoided" Calculations from Two Chemistry-Climate Models. *Scientific Reports*. 9, 1–13 (2019).

77. O. Morgenstern, R. McKenzie, A. van Dijk, P. Newmand, in 2014 UV Workshop (NIWA), (2014). Available at https://niwa.co.nz/sites/niwa.co.nz/files/Morgenstern_UV%20Workshop_2014_World_Avoided_v2.pdf.

Chapter 2

Translating the planetary boundaries framework to New Zealand

2.1 Ethical, normative and scientific principles for setting targets for New Zealand

For the planetary boundaries framework to inform national-level policymaking, it needs to be translated to the respective scale and context, so it can serve as a benchmark for national environmental performance. There is no global consensus on what can be considered a fair distribution. Individual countries have their own perspectives of what can be considered fair, and various approaches, involving normative choices, can be applied to allocate global budgets to the national level.

Fair and equitable allocation of global budgets or distributive fairness has been discussed at length in the climate change literature (e.g.[1]). These approaches either allocate the global budget or the required global reductions in the global overshoot to individual countries. Allocation strategies thereby either establish a nation's right to use a specific share of the global safe operating space or establish a duty to contribute to mitigation of the global overshoot of the safe operating space.

These approaches are based on one or more equity principles, i.e., general concepts of distributive fairness.

Equity principles discussed in the scientific literature[2] that can be applied when allocating the global safe operating space for setting national targets include:

Equality. This refers to a common understanding in international law that each human being has equal moral worth and thus should have equal rights. This is generally translated into all people having equal rights to use the atmosphere and the Earth system.

New Zealand currently accounts for 0.06% of the global population[3]. Therefore, based on per capita allocation, New Zealand's "fair share" of the Earth system, resources, and remaining emission budget is 0.06%.

Responsibility. This relates a country's relative contribution to environmental change to their level of responsibility for solving the problem. It applies the "polluter pays" principle. In the climate change context, this principle is generally translated by relating a country's emission reduction objective to its historical contribution to global emissions or warming.

Assessing national historical responsibility requires globally harmonised data on metrics of contribution to environmental change, for example, emissions, pollutants or resource use. The relatively long historical record of global carbon emissions at national scales is well suited for such a translation in the climate change context. In this case, the responsibility principle is translated by relating a country's emission reduction objective to its historical contribution to global emissions or warming.

Over the period 1959–2017 a total of 1,287 $GtCO_2$ was emitted globally,[4] where New Zealand's territorial emissions (direct emissions generated by activities within a given country) were responsible for 1.45 Gt (0.11%). Based on this cumulative emissions accounting of historic responsibility, New Zealand's "fair share" of global emissions reduction objectives translates to 0.11%.

Capability. This is also referred to as **capacity** or **ability to pay.** It refers to the responsibility of a country to contribute to solving environmental problems. This principle is generally translated into the greater a country's capacity to act or pay, the greater its share in the mitigation/economic burden.

Such ability to pay can be inferred by a country's nominal gross domestic product (GDP), a measure of national wealth based on the size of the economy, with straightforward comparison between countries. New Zealand's current (2017) nominal GDP accounts for 0.23% of the world's economy.[5] Distributing the global overshoot based on countries' share in global GDP, New Zealand's share would translate to 0.23%, dependent on the GDP-metric chosen.

Sovereignty, also referred to as **acquired rights.** This refers to the principle of all countries having the right to use the ecological space, justified by established customs and usage. In the climate change context, this principle is generally translated into allocation of global emission allowances proportional to current national emission levels. In the broader Earth-system change context, allocation of resource-use allowances would similarly be proportional to current share of the global footprint.

The current state of New Zealand's territorial usage of the Earth system, considering the metrics applicable to the planetary boundary framework, is outlined below. Available data, described in Appendix 1, is not temporally consistent across all variables, so the "current state" is the most current year on record, indicated in parentheses.

- CO_2 emissions: 0.10% of global emissions (2017)[4]
- Fertiliser applications:
    - Nitrogen: 0.34% of global nitrogen fertiliser use (2016)[6]
    - Phosphorus: 1.74% of global phosphorus fertiliser use (2016)[6]
- Freshwater use: production usage: 0.13% of global freshwater use (2013)[7]

The sovereignty principle can also be applied according to allocations of spatial equity. For example, the territorial endowment of nations and the spatial extent of land-based variables, like forest and agricultural areas. These allocations can be translated into all nations having spatially proportional rights to use the atmosphere and Earth system, according to the chosen metric.

New Zealand's territorial endowment accounts for 0.20% of the global (ice-free) land area.[6] Therefore, based on the sovereignty principle, and allocated based on land area, New Zealand's "fair share" of the Earth system, resources, and remaining emission budget is 0.20%.

Right to development, also referred to as **needs.** This refers to the interests of poor people and poor countries in having their basic needs met, as a global priority. In the climate change context, this principle is generally translated into the least capable countries being allowed to have a less ambitious reduction target, in order to secure their basic needs. It is thereby closely linked to the capability principle. Assessing New Zealand's needs and rights to development in comparison to other nations is a nontrivial social justice effort, which is outside the scope of this report.

Cost-effectiveness. This refers to taking action where it is most cost-effective. In the climate change context, this principle is usually translated into equal marginal costs. Assessing the cost-effectiveness of emissions reduction and other environmental efforts in New Zealand compared to other countries is a nontrivial economic effort, which is outside the scope of this report.

Ultimately, deciding on an allocation approach is a political decision, which then must be supported by the necessary globally harmonised data. In this report, we use per capita allocation, based on the **equality principle** as a logical starting point for this first assessment of New Zealand's safe operating space. This translation is methodically simplistic, easily understood, and arguably the most objective and apolitical approach. For land-use change and biogeochemical flows, we also consider allocation based on land area, presenting these results as complementary to the per capita allocation.

2.2 Production - and consumption-based perspectives

The environmental pressure generated by a nation can be analysed using two complementary approaches. The *production-based* approach, also known as "territorial accounting", is straightforward: it is the direct environmental pressure generated by activities within a given country. In New Zealand's case, this might include, for example, all emissions generated by the combustion of fossil fuels within its national borders.

A complementary *consumption-based* approach extends production-based analysis to include New Zealand's environmental pressures transmitted through the international trade of goods and services. For instance, a car sold in New Zealand may have been produced in a foreign country. It would have been manufactured within a different energy generation system, using materials sourced from further countries along an extended supply chain. Consumption-based accounting sums the total environmental pressures of each supply chain, then allocates these to the location of final consumption, i.e., New Zealand. Conversely, goods that are produced in New Zealand and then sold to foreign consumers, such as agricultural produce, would be "subtracted" from its environmental balance sheet.

In global studies of consumption-based environmental accounting, environmental pressures allocated to wealthier countries tend to *increase*, relative to production-based

accounts.[8] In contrast, poorer countries tend to consume a smaller proportion of international trade, and rather produce goods for export. Under a consumption-based approach their allocated environmental pressure tends to *decrease* relative to production-based accounts.

The situation for New Zealand may be somewhat different, as a non-trivial fraction of its economy is dedicated to agricultural production and export. New Zealand's top earning export commodities are dairy, meat and forest products, with major trade partners in China, Australia, the United States and the EU.[9] It is therefore likely that a high proportion of domestic land use and agricultural impacts would be allocated to consumers outside of New Zealand.

On the flip side, New Zealand imports a large volume of manufactured goods, in particular vehicle parts and mechanical machinery.[9] Since these goods have energy intensive supply chains, New Zealand is likely to remain consistent with other wealthy countries for climate impacts: allocated environmental pressures will increase from a consumption-based perspective.

2.3 Data material, analysis and caveats

The data for this analysis (excluding the food systems chapter) comprises three main sources. First, we examined international datasets for estimating production-based environmental pressures: the EDGAR database of emissions from fossil-fuel combustion;[10, 11] the Food and Agriculture Organisation of the United Nations database of land and fertiliser use;[6] as well as population and GDP data from the United Nations Population Division[3] and the World Bank.[5]

The final data source is the Eora database of trade and environmental accounts. Eora is a multi-region input-output table – an accounting framework that traces the flow of goods between sectors and countries in a single consistent global database.[12] The trade component of Eora is linked to estimates of environmental pressure in each country, including emissions from fossil-fuel combustion,[13] fertiliser use,[14] land use and water use.[7] Data on these environmental pressures are linked to the sources described above and are embedded within the Eora database. Using this framework, we estimate consumption and production-based accounts of environmental pressure for New Zealand based on the reference year 2015, which is the most current year on record in the Eora database. New Zealand's current (2018) population is nearly 4.8 million and in 2015 the population was just over 4.6 billion[3], in both years accounting for 0.06% of the global population.

There are various sources of uncertainty inherent in benchmarking national environmental pressures. Estimates of carbon emissions are derived from underlying energy use data. They have a comparatively lower degree of uncertainty, due to a high level of standardisation in national energy statistics and the direct link between fuel combustion and emissions. There are higher uncertainties for nitrogen and phosphorus emissions and water use, as the links between available data (e.g., product sales) and impacts are less direct. We expand on data caveats in the annex, particularly regarding nitrogen and phosphorus applications. Illustratively, the IPCC 5th Assessment Report uses uncertainty ranges of ±8% for fossil CO_2, ±20% for CH_4, ±30–90% for N_2O and ±50–75% for land-use change emissions.[15] Thus, caution is required when interpreting environmental impacts on land especially, as well as biogeochemical flows.

Consumption-based analysis raises additional data quality concerns, as it relies on an extended and consistent dataset of trade flows and environmental accounts across all countries. However, as a country with relatively high-quality national accounts and statistics, the additional source of error here is unlikely to be higher than that of the aforementioned environmental accounts, which are used as inputs to the analysis.[12]

2.4 Translation method

The equality principle views the Earth system as a global commons[2], with every individual having equal rights to use its resources and having equal responsibility in conserving it. Every global citizen has an equal share. In this study we apply two approaches to translate the equality principle into national fair shares, based on population as well as land shares, which we refer to as **equal-per capita** and **equal-per-area** allocations.

The **equal-per-capita** allocation is based on current population estimates. First, at the planetary scale, the annual (i.e. biogeochemical flows, freshwater) and cumulative (i.e. climate change) budgets of the boundary control variables are translated into individual person shares (per capita shares). Next, the national scale is aggregated by assigning a country an equitable share based on its population. The per capita shares are multiplied by New Zealand's population to assign the national share. The **equal-per-area allocation** is based on national land area of the global total. First, at the planetary scale and for boundaries with annual budgets, the boundary control variables are translated into individual land shares. For example, nitrogen applications per hectare (ha) of cropland (per area shares). Next, the national scale is aggregated by assigning a country an equitable share based on its total area. In this case, New Zealand's current cropland area is just over 26 million hectares (ha), accounting for .04% of global cropland.[6]

Some boundaries are assessed based on indices (i.e. biosphere integrity) or percentages of land (i.e. land system change). For these boundaries, the global and national shares are allocated in the same way, according to the same indices or percentages.

The aim is to frame the share – and responsibility – to a country (made up of individuals / land area) rather than on each individual person or land unit.

2.5 Status of five assessed planetary boundaries

Here we translate each planetary boundary to the national scale and assess whether the boundary has been transgressed or not. The boundaries are a diagnosis of human perturbation of components of a complex Earth system. They are not stand-alone targets in themselves.

2.5.1 Climate change

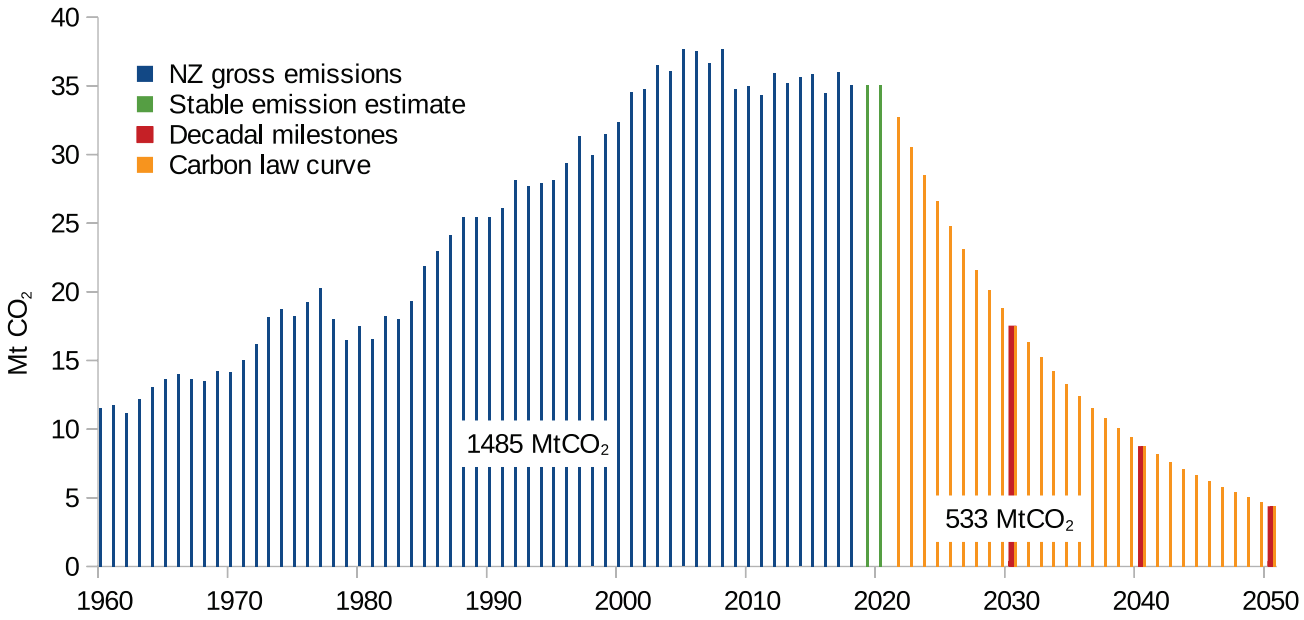
The climate change planetary boundary described by change in radiative forcing and atmospheric CO_2 concentration has been transgressed.[16, 17] Returning to the safe operating space will require immediate reduction of emissions to stabilise the climate.

In this analysis we consider only CO_2 emissions, not the full complement of greenhouse gases (CH_4, N_2O, F-gases) that influence warming. While greenhouse gas emissions could be aggregated using global warming potentials (GWPs), it is not possible to relate these aggregated GHGs to a fixed carbon budget, due to the different lifetimes of non-CO_2 GHGs in the atmosphere. This has clear implications for New Zealand's transgression of the climate boundary, due to its relatively large non-CO_2 emissions impacts – an issue we discuss further in section 2.7.

The SR15 estimates a range of carbon budgets for staying under 1.5°C and 2°C guardrails with associated probabilities of climate response (Table 3).[18] The budgets are finite, and assessed from 2018 onwards. For example, in Table 3, the most ambitious carbon budget with 420 billion tCO_2 remaining to be emitted has a 67% likelihood of staying within 1.5°C of warming.

Translating these carbon budgets into national shares must consider the time horizon, the emission pathway, and the resultant annual emission rates. The time horizon is the timeframe in which the budget is used, starting from the current year. For example, the 2050 time horizon aligns with established policy goals and the 2100 time horizon aligns with the Paris Agreement warming guardrails. The emission pathway determines the annual rates, using the entire budget until the time horizon, after which zero gross emissions are implied.

Figure 10: National CO_2 emissions over the historical period 1959–2018, totalling 1485 $MtCO_2$ emitted, followed by the gross emissions component of the carbon law pathway from 2020–2050, whereby current gross emission levels are halved by 2030, halved again by 2040, and again 2050, totalling 533 $MtCO_2$ emitted.



The carbon law pathway, introduced in section 1.4.1, is a scenario of exponential decline in anthropogenic gross emissions in combination with increased negative emissions to reach net-zero by 2050. This gross emission pathway is constructed for New Zealand in Figure 10, with decadal halving from 2020 - 2050, and stabilised emissions are assumed from 2018 - 2020. The emissions from each year are summed to provide the historical cumulative emissions (1485 $MtCO_2$) and the emission under the future pathway (533 million $MtCO_2$). The remaining global carbon budget under this scenario aligns with the SR15 budget for staying under 1.5°C warming with 50% probability.

Considering such emissions pathways are highly relevant in policy and planning contexts. However, with a cumulative budget, performance in the current years can appear in the safe operating space, as the budget has just begun to be used, despite being on a trajectory to certain transgression. Assessing various pathways of allocation, for example where rates remain constant every year, can be highly instructive in terms of understanding potential for transgression. To do so, the global carbon budgets have been translated to national shares in Table 3, where the SR15 global carbon budgets are reported alongside New Zealand national shares of the global budget.

National shares are found by simply multiplying the per capita allocation (global citizen) by the population of a country. This yields New Zealand's share of the remaining global carbon budget. For example, the most ambitious global carbon budget assessed has a 67% likelihood of staying within 1.5°C of warming (420 $GtCO_2$ remaining), and New Zealand's national share is 0.26 $GtCO_2$ remaining, aggregated nationally per capita.

A current-rates allocation is a business as usual pathway, which extends current emissions into the future until a given carbon budget is spent. This allocation reveals the number of years in which stabilised status quo emissions would be possible before a transgression. This is a charitable allocation in the global context, where emission rates continue to rise. However, this is a plausible allocation for New Zealand where emission rates have stabilised over the last 10 years. The current (2017) emissions rate is 36.2 $GtCO_2\ yr^{-1}$ globally and 36 $MtCO_2\ yr^{-1}$ nationally.[11] Table 4 reports the year of transgression, where the carbon budget is spent under current emission rates, both globally and nationally. If New Zealand's current emission rates continue, the national share of the +1.5°C (67%) warming boundary is transgressed in 2025 and the +2°C (67%) warming boundary is transgressed in 2038.

A **constant-rates allocation** reveals the amount of carbon that could be emitted per year, given a time horizon for using the entire budget, after which zero emissions would be necessary to avoid transgressing the climate boundary. The total carbon budget remaining from 2018 onwards is divided equally across the remaining years in the time horizon. The annual emission rate is constant over the entire period. This is an implausible pathway, requiring an abrupt jump from the current year to the next, and a hard stop of emissions at the end of the time horizon. However, this allocation is effective at translating the cumulative budget into an annual target, which can be considered the mean annual emission goal over the entire period. Assessing the climate boundary is instructive in this allocation, as the highest transgression occurs in the immediate years.

Table 3: SR15 Table 2.2 cumulative global carbon budgets assessed for 2°C and 1.5°C warming guardrails, for two time horizons (2050, 2100), and across three reported climate response percentiles.[18] Per capita allocations (tCO_2 cap yr^{-1}) are assessed based on current (2018) world population, and with a so-called constant-rates allocation, where the remaining budget is used equally per year, with zero emissions implied after the time horizon. The national shares aggregated from the per capita allocation based on New Zealand's current (2018) population.

Remaining carbon budgets from 2018: **equal-per capita allocation**										
Warming	Budget	**33rd percentile**			**50th percentile**			**67th percentile**		
		$GtCO_2$	tCO_2 cap yr^{-1}		$GtCO_2$	tCO_2 cap yr^{-1}		$GtCO_2$	tCO_2 cap yr^{-1}	
			2100	**2050**		**2100**	**2050**		**2100**	**2050**
1.5°C	**Global**	**840**	1.33	3.33	**580**	0.92	2.30	**420**	0.66	1.67
	National	*0.52*			*0.36*			*0.26*		
2°C	**Global**	**2030**	3.20	8.06	**1500**	2.37	5.96	**1170**	1.85	4.65
	National	*1.26*			*0.93*			*0.73*		

Table 4: Time horizon until transgression of the +2˚C and +1.5˚C carbon budgets across three different likelihood estimates of remaining within these temperature goals (based on SR15 Table 2.2).[18]

Warming above pre-industrial levels		Time horizon under current rates		
Percentiles		*33rd*	*50th*	*67th*
Global budget	1.5˚C	2041	2034	2029
	2˚C	2074	2059	2050
National budget	1.5˚C	2032	2028	2025
	2˚C	2053	2043	2038

National shares of the global carbon budget are useful in the local context, but can't be meaningfully compared across countries, as results are biased by population size. Per capita shares are useful in this situation. Based on a constant-rates allocations of the SR15 remaining carbon budgets and current (2018) world population, global per capita emission allocations (tCO_2 cap yr^{-1}) are calculated and reported in Table 3. Figure 11 juxtaposes the historical per capita emissions of the average New Zealander and the average global citizen (1959 - 2017), with the necessary per capita emissions to stay within a given carbon budget. The remaining budget is used equally per year, with zero emissions implied after the time horizon.

Global CO_2 emissions have steadily increased over the past 60 years[11] despite a stabilisation in per capita emissions over the last 10 years, as seen in Figure 11. Global population increase is outpacing emission reduction efforts. New Zealand's annual CO_2 emissions have stabilised over the last 10 years and per capita emissions have been declining since the early 2000's (Figure 11), illustrating that national emissions reduction efforts are outpacing population increase. Despite this promising trend, the per capita emissions of the average New Zealander (7.4 tCO_2) remains significantly higher than the average global citizen (4.8 tCO_2).

For this report, these per capita emissions goals (Table 3) are used to set the climate boundary and assess New Zealand's performance of production and consumption based emissions (Figure 12). The boundary is placed at the per capita emissions corresponding to the constant rates allocation of the carbon budget assessed for the warming guardrail until the 2100 time horizon. Specifically, the boundary is the 67% likelihood of climate response, the zone of increasing risk (uncertainty) is between 33 - 67% likelihood, and the high risk zone is under 33% likelihood. Both the 1.5°C and 2°C warming guardrails are assessed. Appropriately, transgression of this time averaged goal will be high right now, reflecting inevitable future transgressions should the current trajectory transpire.

Figure 11: Global and national per capita emissions (1959–2017), with constant-rates allocations of the SR15 carbon budgets[18], translated to per capita emissions goals from 2018 onward, with a hard-stop once the budget is used.

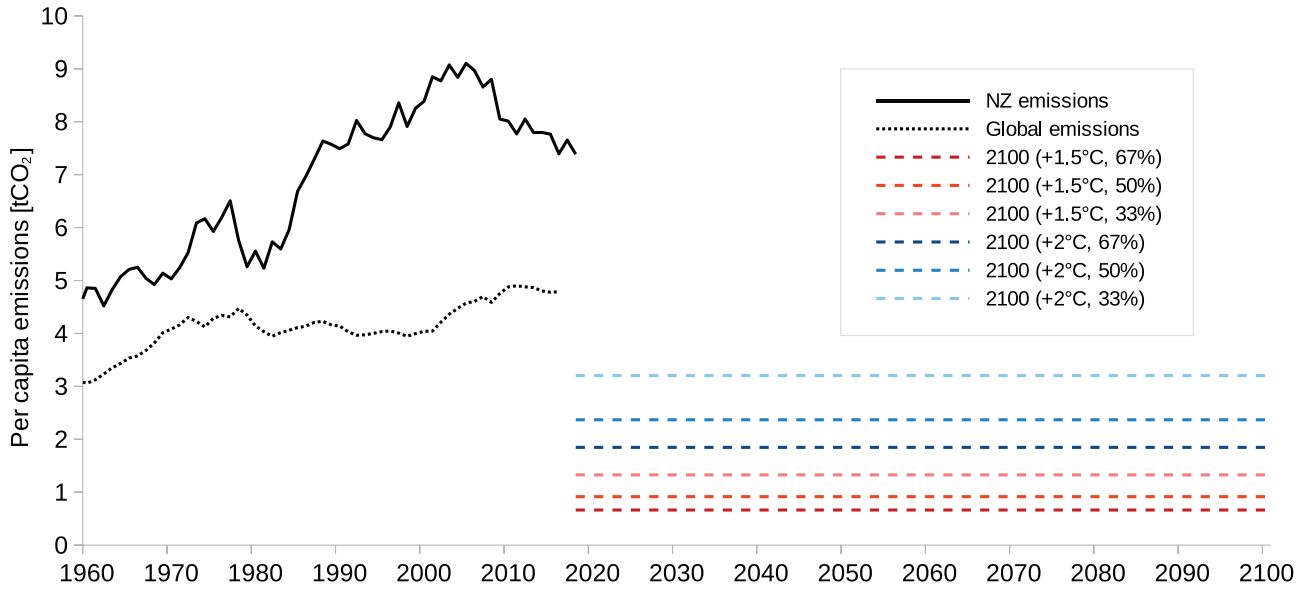
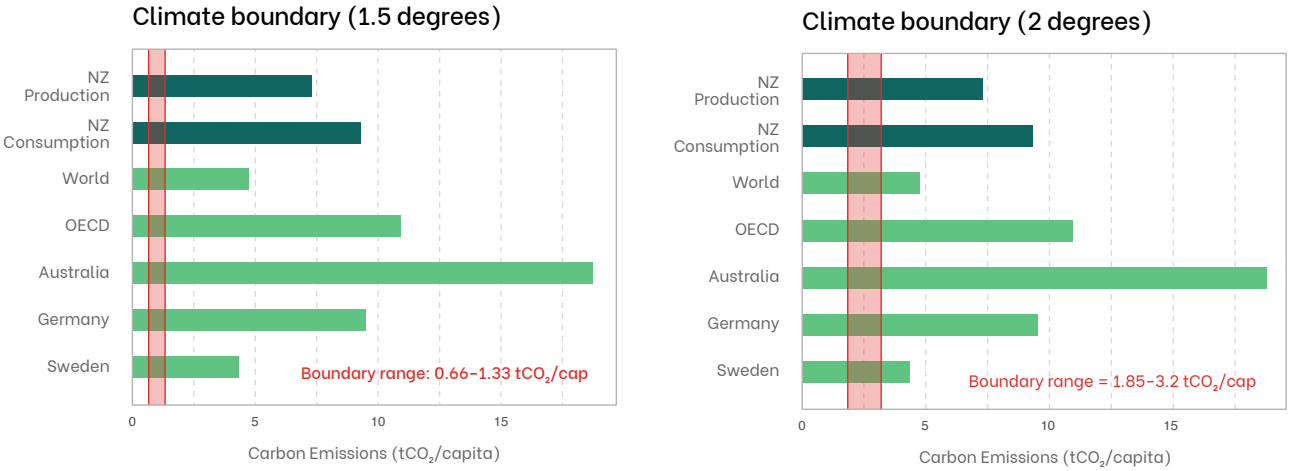


Figure 12: New Zealand's consumption and production-based per capita emissions exceed the national share allocation of the global contribution to climate boundary transgression, assessed based on SR15 carbon budgets for 1.5˚C and 2˚C warming guardrails[18]. The start of the expressed range (red bar) is the boundary, below which is the safe operating space. Within the red bar is the zone of increasing risk (or uncertainty) which corresponds to the climate response percentiles from 67- 33% likelihood, beyond which (>33% likelihood) is the high risk zone. For comparison, global average, OECD and other nations are shown (production only).



New Zealand exceeds all identified climate per capita allocations assessed for this report, from lower to upper estimates of certainty in avoiding temperature overshoot, for both 1.5°C and 2°C goals. The climate boundary is exceeded to a large degree, with recent production-based emissions of approximately 7 tCO_2 cap yr^{-1}, compared to the most stringent target of 0.66 tCO_2 cap yr^{-1} that would offer a "safe" (67%) chance of remaining below 1.5°C.

In terms of consumption-based emissions, New Zealand is similar to many other advanced economies: when the extended supply-chain of production activities is allocated to consumers, the total environmental pressure induced by New Zealand increases. Here we see a difference of approximately 2 tCO_2 cap yr^{-1}, with total emissions rising to 9 tCO_2 cap yr^{-1}. New Zealand is even further away from a safe planetary space in this perspective.

Taking an international view, New Zealand's production and consumption emissions are still below that of production emissions in high-emitting countries such as Australia, as well as the OECD average. But they are also substantially higher than the global average per capita value, which sits just below 5 tCO_2 cap yr^{-1}.

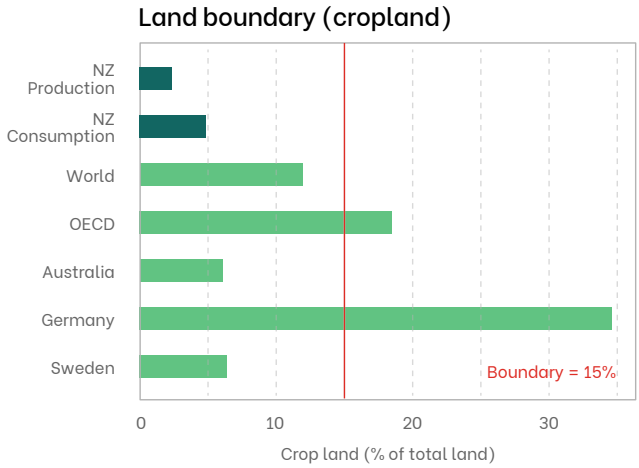
2.5.2 Land-system change: land-use change

Land-system change is evaluated both in terms of the initial cropland variable and the revised forest cover variable. Considered together, these metrics show a more complete view on land-system change in New Zealand.

The initial "change in land use" boundary limits conversion to cropland to no more than 15% of global ice-free land surface.[16] According to FAO (2017),[6] the global proportion of land converted to cropland is 12% (~1.6 billion ha) and the national proportion of land that has been converted to cropland is 2.4% (~645,000 ha), both within the 15% boundary (Figure 13).

According to the cropland criteria (15%), the land-system change boundary would be the only boundary that New Zealand manages to remain within. New Zealand's crops cover just 2.4% of its total land area. From a consumption-based perspective, this footprint increases to approximately 5% (as a fraction of New Zealand's domestic land area). Both measures remain within the international boundary of 15%. Indeed, the international limit has not yet been reached at a global level (12%).

Figure 13: Land boundary based on cropland usage. For comparison, global average, OECD and other nations are shown (production only).



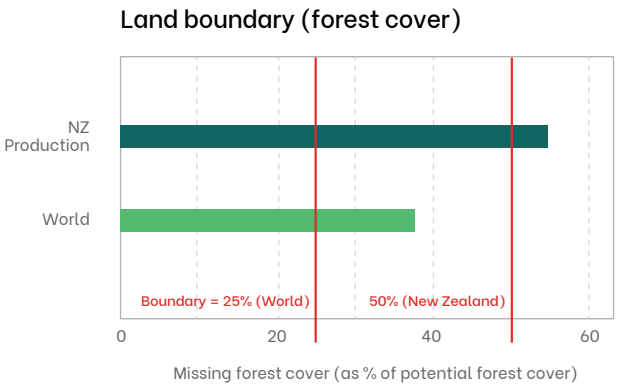
The cropland boundary does not fully represent pressures on land. For instance, it is estimated that 40% of New Zealand is currently exotic pasture,[19] i.e., human-induced land use that is not captured in the cropland definition. While this distinction might not sway global results, for New Zealand, the land-use proportion is significant.

The alternative and updated approach is to assess the land-system change boundary using a forest cover metric, based on the extent of original (potential) forest cover.[17] For global forest extent, the biome specific boundaries are averaged, setting the global boundary at 75% of original (potential) forest cover remaining, with rising risk down to 54% remaining. The temperate forest biome boundary is relevant to New Zealand, set at 50% remaining, with rising risk down to 30% remaining.

Global potential forest area is approximately 5.9 billion hectares.[20, 21] The current proportion of land covered in forest is 30.7% (~4 billion ha)[6], meaning 68% of original forest coverage remains. This transgresses the planetary boundary of 75% remaining.

Approximately 85% of New Zealand's land area was originally forested (22.4 million ha)[22], and current forest cover is 39%[6], equating to 45% of potential forest cover. Therefore, New Zealand's temperate forest biome boundary of 50% remaining (11.9 million ha) has been transgressed. The uncertainty zone around this boundary is down to 30% remaining (6.7 million ha), which New Zealand is still within.

Figure 14: Land boundary based on forest cover (territorial/production only), with global average for comparison. Based on original forest extent, the global boundary is placed at 25% missing, and New Zealand's biome boundary is placed at 50% missing.



This evaluation is sensitive to the reliability of potential forest cover estimates. The boundary considers the total spatial extent of forest, regardless of location (changes) or species characteristics (changes). Of the 10.2 million ha of remaining forest in New Zealand, just 30% is considered indigenous forest.[19] The forest boundary does not distinguish between indigenous and exotic forest. Such nuances are relevant regionally and better captured with the addition of biome-specific boundaries.

Ultimately, the land-system change boundary is focused on forest-related biogeophysical processes with global implications, so in this regard, quantification of forest extent is appropriate and sufficient for analysis of land-system change globally. In addition, forest "quality" is more relevant to – and considered in the analysis of – the biosphere integrity boundary.

2.5.3 Freshwater use

At the global scale, the freshwater control variable is defined as the maximum amount of consumptive blue-water use. Consumptive use of blue water includes rivers, lakes, reservoirs and renewable groundwater stores. The global boundary was originally set at 4,000 $km^3\ yr^{-1}$ and has remained at this estimation after recent revisions.[16,17] The difficulty of and utility in estimating a planetary limit to freshwater use has been widely discussed and challenged, given the substantial regional impacts to aquatic ecosystems of transgressing the freshwater boundary.[23]

A freshwater planetary boundary is inherently focused on global-scale feedbacks, like moisture recycling, such that a transgression in one area might have global impacts. However, it can be argued the local-scale aquatic ecosystem functioning can have global-scale consequences, as sustaining these ecosystem processes supports the resilience of inland and coastal landscapes. Additionally, degradation of local drinking water resources would put pressure on water resources elsewhere.

With this in mind, river-basin-scale control variables have been developed, based on the concept of "environmental water flow" (EWF), which is defined as the minimum amount of blue water that must remain within a river basin.[23] Withdrawals of water for household, industry and livestock use are the main source of pressure on maintaining adequate EWFs. Geomorphological changes such as channelisation, reservoirs, hydropower operation and flood control also affect EWFs.

The river-basin-scale metric is expressed as an average percentage of mean monthly flow, where a river basin's EWF plus water withdrawals must add up to the mean monthly flow. In other words, once water withdrawals have been accounted for, the EWF is what remains in the river (low flow), making it the minimum amount of water necessary to sustain the ecosystem. EWFs should reflect the quantity, quality and temporal aspects (timing, duration, frequency) of blue-water flows required to sustain freshwater, estuarine and near-shore ecosystems.[23] In this way, the EWF metric is described as an aggregated proxy for both baseflow (low-flow) and stormflow (high-flow) requirements.

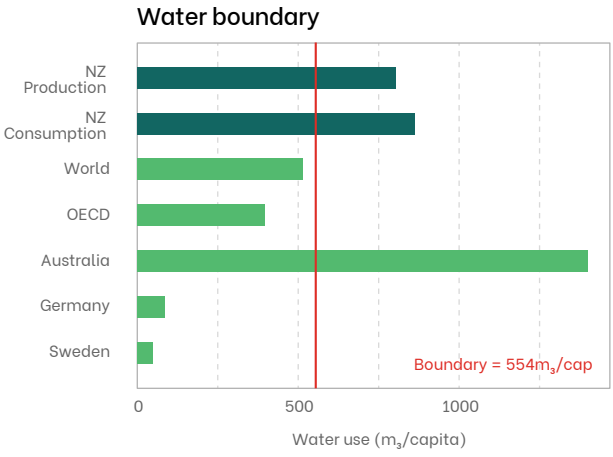
There is potential for such a national assessment of EWF status of New Zealand's river basins, though it is beyond the scope of this report. Comprehensive data exists on licensed withdrawals, which effectively quantify the maximum amount of water that is permitted for use. Though the exact withdrawals could be more or less, it is important to understand whether the current licensed withdrawals are within the global and regional safe operating space.

For this report, and as a starting point, an equal-per capita allocation is applied to the global freshwater planetary boundary to determine the national share. The global limit is estimated at 4,000 $km^3\ yr^{-1}$ (4 trillion $m^3\ yr^{-1}$). This equates to a global per capita limit of 555 m^3 cap yr^{-1}, with an uncertainty zone up to 832 m^3 cap yr^{-1}. Therefore, the national freshwater budget, based on population, is 2.5 billion $m^3\ yr^{-1}$ with an uncertainty zone up to 3.8 $m^3\ yr^{-1}$.

Current estimates place New Zealand's production-based water use at approximately 803 m^3 cap yr^{-1}, exceeding the translated water boundary of 554 m^3 cap yr^{-1}. From a consumption-based perspective, water use increases, albeit marginally, to 861 m^3 cap yr^{-1}.

Since water use is relatively difficult to measure at a national and international scale, these estimates are derived from national production data in agricultural, industrial and domestic sectors and average rates of corresponding water use. This includes, for example, blue water for animal rearing.[7] The data places New Zealand very high on the scale of per capita water use, beyond the OECD average and significantly exceeding levels in some European countries.

Figure 15: Freshwater Boundary based on -per capita water usage. New Zealand's consumption and production compared with the global average, OECD and other nations (production only).



2.5.4 Biogeochemical flows: nitrogen and phosphorous

The industrial and intentional biological fixation of nitrogen from atmospheric N_2 is responsible for the majority of reactive nitrogen input to the Earth system. The main near-term environmental impacts resulting from anthropogenic N fixation are increased atmospheric NH_3 concentrations, radiative forcing by N_2O, drinking water contamination by NO_3, and eutrophication of aquatic ecosystems.[24] Together, these kinds of changes in the flows of nutrient elements affect long-term Earth-system functioning and resilience, changing biodiversity, altering the carbon cycle and amplifying or reducing the impacts of climate change.

Potential boundaries are estimated for N fixation rates ranging from 20 to > 130 Tg N yr^{-1} across the above-mentioned set of environmental concerns (1 Tg equals 1 billion kg). The climatic (N_2O) safe space has the strictest boundary at 20 Tg N yr^{-1}, with the other potential N boundaries ranging from 62–133 Tg N yr^{-1}r.[24]

The rationale in Steffen et al.[17] for setting the nitrogen boundary is as follows: the most conservative boundary estimation is the climate-related potential N boundary, which can be assumed to be accounted for in the climate change radiative forcing boundary estimation, so it can be argued that the next lowest boundary estimation is appropriate for setting the N boundary.[17] This is the boundary estimation connected to the eutrophication of aquatic ecosystems at 62 Tg N yr^{-1}.

The control variables for biogeochemical flows are the flow of N and P from soil to the freshwater system, as this is directly related to the risk of eutrophication. For N, this was adapted to the application rate of intentionally fixed reactive N to the agricultural system, as this is more easily measured and traced. The phosphorus boundary is set following the same rationale.[17] However, we also report from a dedicated study on N emissions, which estimates international N losses to water and air, and provides crucial context to these results.

The global boundary for intentional nitrogen fixation is 62 Tg N yr^{-1} with a zone of uncertainty up to 82 Tg N yr^{-1}. The global boundary for phosphorus flows is 6.2 Tg P yr^{-1} with a zone of uncertainty up to 8.2 Tg N yr^{-1}.[17]

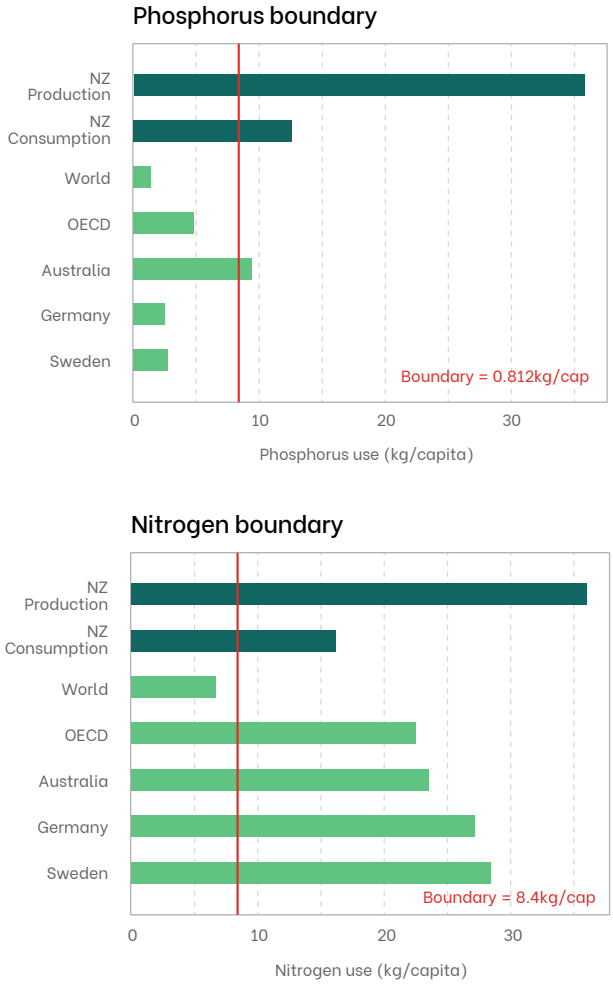
Both equal-per capita and equal-per-area allocation methods are used for calculating global shares of biogeochemical flows, based on population (8.4 kg N cap yr^{-1}; 0.84 kg P cap yr^{-1}) and based on cropland area (39.7 kg N ha yr^{-1}; 3.97 kg P ha yr^{-1}), where 1 Tg = 1 billion kg.

Translating biogeochemical flows to the national scale is done based on New Zealand's current population (38.8 million kg N yr^{-1}; 3.88 million kg P yr^{-1}) as well as cropland area (25.6 million kg N/yr; 2.56 million kg P yr^{-1}). The per capita allocations speak to a population's consumption, while per hectare of cropland allocations speak to an area's production.

For nitrogen and phosphorus nutrient applications, the indicators we use in Eora draw from spatially explicit fertilizer application data, aggregated to a national level.[25] Application refers to the quantity of nutrients applied to cropland, and does not include manure from livestock, industrial uses, and non-cropland applications.

New Zealand's "fair share" of biogeochemical flows is larger when based on population rather than per cropland area. The per-area allocation situates New Zealand's share based on its holding of global cropland. Although it is known that 40% of New Zealand land area is pastureland, it is not part of the internationally harmonised cropland data that is the basis of the global analysis. In the absence of equivalent pastureland information for every country in the world, we conduct this limited analysis on the existing data, and acknowledge this limitation. Given the per-area allocation is less meaningful for the New Zealand context, the analysis continues with the equal-per capita allocation. New Zealand exceeds its national share of both the phosphorus and nitrogen boundaries, placing it far beyond the guardrail in terms of biogeochemical flows.

Figure 16: Biogeochemical flows boundaries based on per capita nitrogen (upper panel) and phosphorus (lower panel) usage. New Zealand's consumption and production are compared with the global average, OECD and other nations (production only).



From a production-based perspective, New Zealand exceeds OECD countries on both measures – reflecting its role as an agricultural producer and exporter. When phosphorus and nitrogen application impacts are allocated to consumers, New Zealand's responsibility declines, but remains substantially beyond a safe operating space.

Careful interpretation is needed of the nitrogen and phosphorus boundaries, especially when translated at national levels. The global boundary is essentially set based on a non-human world baseline. Therefore, any anthropogenic influence on biogeochemical flows causes a boundary transgression. Additionally, the global boundary does not account for nitrogen use efficiency. More efficient agricultural systems can significantly reduce leaching into water systems allowing for a more generous allocation.

The nitrogen and phosphorus applications here refer to those on cropland only, and hence exclude New Zealand's relatively large share of livestock production and its associated impacts. However, a dedicated study on international nitrogen emissions (not applications) linked to all land-use types and non-agricultural sectors, also reflects the impacts we see here: New Zealand's consumption based nitrogen emissions are within the range of other developed countries (~48kg N cap yr^{-1}) and are beyond a safe boundary for global emissions (3.9kg N cap yr^{-1})[25]; New Zealand is also the 6th highest global exporter of nitrogen emissions on an absolute basis, confirming the direction of trade (high production, high exports) and the high degree of nitrogen-related impacts for a small country. The primary commodities and trade flows associated with these domestic impacts are meat and meat products (principally lamb meat, bovine meat, and offal).[14]

2.5.5 Biosphere integrity

The biosphere integrity planetary boundary was initially proposed in relation to the loss of genetic biodiversity.[16] The update to the framework also includes measures of functional groups of living organisms, to better capture the Earth-system role of the biosphere at sub-global levels.[17]

Genetic diversity accounts for the long-term resilience of the biosphere to either withstand or adapt to gradual abiotic change. Functional diversity accounts for the various roles of the biosphere in global processes.

Functional diversity losses are measured at the biome scale, with the control variable Biodiversity Intactness Index (BII), a measure of remaining terrestrial biodiversity at sites exposed to human-related pressures.[26] BII can measure both species richness (how many kinds of organisms are present) and abundance (how common or rare they are), relative to a baseline with minimum human impacts.[27] Global estimates of BII combine world conservation data with models of overall abundance, models of abundance-based compositional similarity and global estimates of land use and other pressures.

Species richness is tied to ecosystem resilience, though little is known about how much and what types of biodiversity can be lost before the functioning of an ecosystem is adversely impacted. Species abundance is tied to ecosystem scale changes in populations as a result of human activities.[27] The BII ranges from 0–100, as compared to a pre-industrial-era reference point, with 100 indicating richness or abundances across all functional groups at pre-industrial levels, and where 0 would indicate complete human modification. It is possible to have a BII value higher than 100, in instances where species richness or abundance is higher than the pre-industrial reference point. Therefore, with the BII, a loss in abundance of a given species can be compensated for by the increase in another.

Islands are often home to a disproportionate number of endemic species compared to mainlands. The oceanic islands may have relatively low overall species diversity because of their isolation, and the pattern and timing of human pressures can be very different. Sanchez et al.[28] updated the methods previously used to estimate BII globally to allow pressure effects to differ between islands and mainlands. For this report, we utilise a 2005 snapshot (the most recent year available) of BII abundance and richness adjusted for islands;[28] both metrics are reported, however, transgression is only assessed based on BII abundance, in line with the planetary boundary framework.

The global boundary for BII is set at 90% maintained intactness, with a very broad uncertainty zone from 30–90%.[17]

Mean Species Abundance (MSA) is another widely used measure, especially useful in global impact assessment modelling. It is an estimate of the mean abundance of original species in a disturbed situation relative to their mean abundance in an undisturbed reference situation.[29] MSA is similar to BII, with the main difference being that MSA does not include increase in species abundance from undisturbed to disturbed locations; a species gain does not compensate for another species loss. Based on model analysis of the relationship between biodiversity losses and multiple pressures, not just land use as for BII, a global boundary based on MSA has been set at 72% maintained abundance.[2]

Both biosphere integrity boundaries are indices, and therefore do not scale based on per capita or area measures. With the equal allocation criteria, global boundaries translate directly to national scales. Spatially averaged national and global summary statistics for all BII and MSA metrics are reported in Table 5. On average, and across metrics, New Zealand's biosphere integrity is less intact (51–58) than global averages (71–75).

Nationally and globally, the 90% BII boundary is transgressed, as well as the 72% MSA boundary. The spatial patterns of BII and MSA for New Zealand can be seen in Figures 21 and 22, respectively. Figure 23 shows the scale of boundary transgression, depicted as reduction in biodiversity intactness (i.e., setting the boundary marker at 10% loss rather than 90% maintained) so that the chart shows transgressions of the boundary in the same format as for the other issues, with longer bars showing a worse outcome.

Table 5: National and global values for all BII and MSA metrics.

Biosphere Integrity Metrics		BII		MSA
		Abundance	*Richness*	
Global	**average**	**75**	**73**	**71**
	min	17	12	6
	max	124	107	98
	std dev	19	20	23
NZ	**average**	**58**	**51**	**56**
	min	28	27	22
	max	85	85	85
	std dev	10	11	22

Figure 17: Spatial patterns of the Biodiversity Intactness Index for species abundance in New Zealand.

Figure 18: Spatial patterns of Mean Species Abundance in New Zealand.

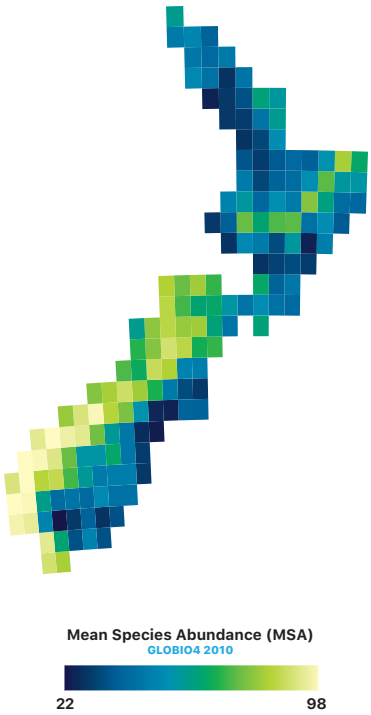
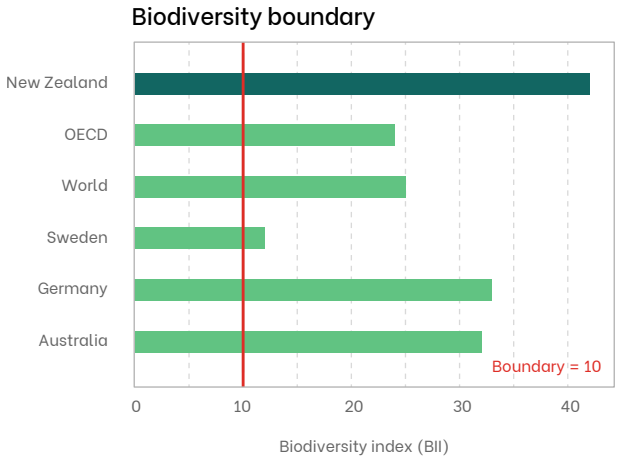


Figure 19: Transgression of the biodiversity boundary based on the biodiversity intactness index (BII) for the species abundance metric. So that the chart matches the format of other boundaries, with longer bars showing greater exceedances of the allocation, the boundary maintaining 90% BII has been inverted to show the reduction in intactness.



2.6 Approaches applied in this study

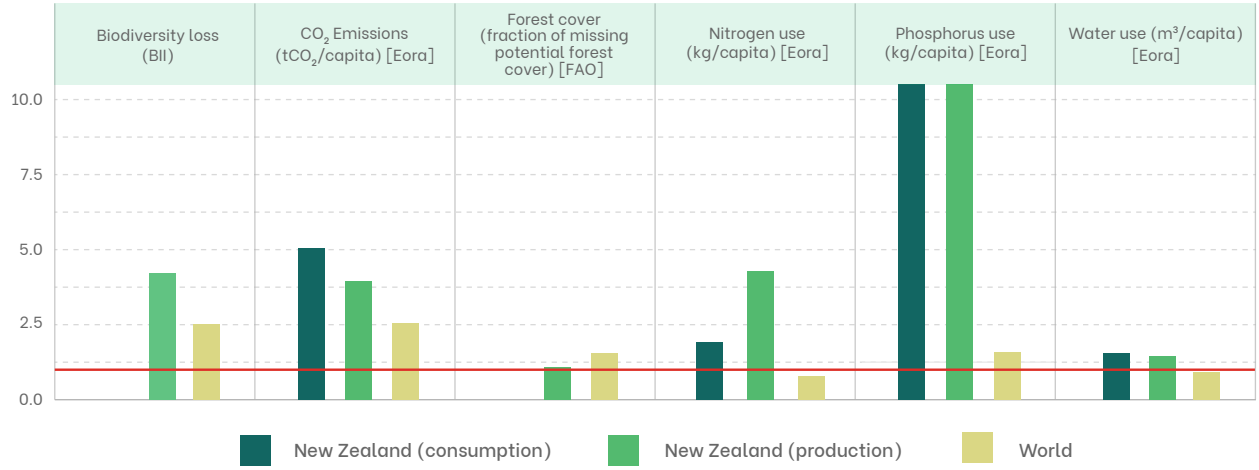
Table 6: Summary of control variables, global and national budgets.

Planetary boundary				Global budget		National budget	
Boundary	**Control variable**	**Global limit**	**Equal per capita**	**Equal per area**	**Equal per capita**	**Equal per area**	
Climate change	CO_2 emission (+1.5˚C)	420–840 $GtCO_2$*	0.66–1.33 tCO_2 cap yr^{-1}**	--	3.1–6.3 million CO_2	--	
	CO_2 emission (+2˚C)	1170–2030 $GtCO_2$*	1.85–3.2 tCO_2 cap yr^{-1}**	--	8.7–15.1 tCO_2	--	
Land-use change	Cropland conversion	15%	--	1.96 billion ha	--	3.95 million ha	
	Forest remaining	*Global*	75%	--	4.43 billion ha	--	10.47 million ha
		Temperate	50%	--	--	--	6.99 million ha
		Boreal	85%	--	--	--	--
		Tropical	85%	--	--	--	--
Freshwater use	Blue-water use	4 trillion m^3 yr^{-1}	555 m^3 cap yr^{-1}	--	2.51 billion m^3 yr^{-1}	--	
Biogeochemical flows	N application	62 billion kg N yr^{-1}	8.4 kg N cap yr^{-1}	39.7 kg N ha yr^{-1}°°	38.8 million kg N yr^{-1}	25.6 million kg N yr^{-1}	
	P applications	6.2 billion kg P yr^{-1}	0.84 kg P cap yr^{-1}	3.97 kg N ha yr^{-1}°°	3.8 million kg P yr^{-1}	2.56 million kg P yr^{-1}	
Biodiversity loss	BII maintained	90% (30–90%)	--	--	--	--	
	MSA maintained	72%	--	--	--	--	

*range across 33–67% likelihood in climate response; **equal allocation to 2100 time horizon; °°per ha of cropland

2.7 Conclusions

Figure 20: Normalised boundaries and environmental impacts of New Zealand. Note that the values for phosphorus use exceed the axis limits (New Zealand consumption = 19, production = 54).



Following the equality principle, and according to two allocation approaches based on population and land area, New Zealand exceeds its national allocation, or fair share, of the planetary boundaries for biodiversity loss, climate change, land use change, biogeochemical flows and freshwater use (Figure 20).

New Zealand's fair share of the land-system change and freshwater boundaries are exceeded the least. Based on a temperate forest-cover measure of land disturbance, New Zealand just transgresses the boundary. However, with an estimated 43% of total land area in agricultural use, 55% of potential forest cover removed, and a significant transgression on the biosphere integrity boundary, our analysis indicates that current land-use patterns are far from sustainable. These land-use patterns are likely having local impacts on water quality and quantity which are not captured by the global scale freshwater boundary. To support long-term sustainable water use, we suggest further analysis of environmental water flows on a catchment by catchment basis.

Similarly, while New Zealand's current per capita CO_2 emissions transgress the climate boundary, this remains a partial estimate of climate impacts due to the absence of non-CO_2 greenhouse gases (GHGs) in this analysis. New Zealand's relatively high land-use impacts, which are typically linked to CH_4 and N2O emissions, would suggest an even greater exceedance of the climate boundary – although this would require confirmation using modelling analysis that goes beyond the carbon budgeting approach employed here.

Overall, we observe that New Zealand's greatest transgression of its fair share among the planetary boundaries lies in biogeochemical flows, and specifically phosphorus use. From a consumption-based perspective, much of this impact would be allocated towards export markets; yet even then phosphorus use remains exceedingly high. This holds true for both fertilizer applications to cropland (shown in Figure 21), and nitrogen emissions from all land types including livestock.[14] Beyond this, climate impact and biodiversity loss are major concerns. Both exceed global average levels and are substantially beyond a safe operating space.

Figure 21: The radial plots show global (top) and national (bottom) status of five planetary boundaries on a normalised scale. New Zealand exceeds its "fair share" of the global safe operating space for most production-based (territorial) and consumption-based boundaries. The safe zone is depicted in the centre, where the edge of the green circle is the normalised boundary (= 1). After boundary transgression is a zone of increasing but uncertain risks (= 1 - 2). Beyond this is a zone of high risk, depicted by the red line (= 2), which equates to boundary transgression by a factor of 2. From the red line outward, factors of transgression continue approximately according to the white lines. The scale is capped at a factor of 15. Note that phosphorus on the production side is at 55 times transgression and therefore goes off the chart.

References

1. M. Fleurbaey et al., Sustainable development and equity, in *Climate Change 2014: Mitigation of Climate Change* (O. Edenhofer et al. (Eds.). IPCC AR5 (2014).
2. P. Lucas, H. Wilting, Towards a Safe Operating Space for the Netherlands: Using planetary boundaries to support national implementation of environment-related SDGs (2018). Available at https://www.pbl.nl/en/publications/towards-a-safe-operating-space-for-the-netherlands.
3. United Nations, Department of Economic and Social Affairs, Population Division, World Population Prospects: The 2017 Revision, DVD Edition (2017).
4. The Global Carbon Project, available at https://www.globalcarbonproject.org/.
5. World Bank (2019). Available at: https://data.worldbank.org/.
6. FAO (2018). Available at: http://www.fao.org/faostat/en.
7. M. Lenzen, D. Moran, A. Bhaduri et al., International Trade of Scarce Water. *Ecological Economics*, (2013). DOI: 10.1016/j.ecolecon.2013.06.018
8. G. P. Peters, J. C. Minx, C. L. Weber, O. Edenhofer, Growth in emission transfers via international trade from 1990 to 2008. *PNAS USA*. 108, 8903–8 (2011).
9. Goods and services trade by country: Year ended March 2018. Available at https://www.stats.govt.nz/information-releases/goods-and-services-trade-by-country-year-ended-march-2018.
10. M. Crippa et al., Fossil CO2 and GHG emissions of all world countries - 2019 Report, EUR 29849 EN, Publications Office of the European Union, ISBN 978-92-76-11100-9, doi:10.2760/687800, JRC117610 (2019).
11. C. Le Quéré, R. M. Andrew, P. Friedlingstein et al., Global Carbon Budget 2018, *Earth Syst. Sci. Data* (2018). Available at https://doi.org/10.5194/essd-10-2141-2018.
12. M. Lenzen, K. Kanemoto, D. Moran, A. Geschke, Mapping the structure of the world economy. *Environmental Science & Technology*. 46(15), 8374–8381 (2012). DOI: 10.1021/es300171x.
13. K. Kanemoto, D. Moran, E. Hertwitch, Mapping the Carbon Footprint of Nations. *Environmental Science and Technology*, (2016) DOI: 10.1021/acs.est.6b03227.
14. A. Oita, A. Malik, K. Kanemoto et al., Substantial nitrogen pollution embedded in international trade. *Nature Geoscience*. 9(2), 111–115 (2016). DOI: 10.1038/ngeo2635.
15. IPCC, Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (T. F. Stocker et al (Eds.)) (2013).
16. J. Rockström, W. Steffen, K. Noone et al., A safe operating space for humanity. Nature. 461, 472–475 (2009).
17. W. Steffen, K. Richardson, J. Rockström et al., Planetary boundaries: Guiding human development on a changing planet. Science. 347 (2015).
18. IPCC, Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018). Available at https://www.ipcc.ch/sr15/.
19. N. J. D. Singers, G. M. Rogers, A classification of New Zealand's terrestrial ecosystems. New Zealand Department of Conservation (2014).
20. UN Food and Agriculture Organisation, Forest Resources Assessment 2010: Global Tables. (2010). Available at: http://www.fao.org/forest-resources-assessment/past-assessments/fra-2010/en/.
21. N. Ramankutty and J. Foley, Estimating historical changes in global land cover: Croplands from 1700 to 1992. Global Biogeochemical Cycles. 13(4), 997-1027 (1999).
22. Ministry for the Environment, Stats NZ, New Zealand's Environmental Reporting Series: Predicted pre-human vegetation (2015).
23. D. Gerten, H. Hoff, J. Rockström et al., Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Current Opinion in Environmental Sustainability. 5(6), 551–558 (2013).
24. W. De Vries, J. Kros, C. Kroeze, et al., Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Current Opinion in Environmental Sustainability, 5(3–4) 392–402 (2013).
25. EEA, FOEN, Is Europe living within the limits of our planet? An assessment of Europe's environmental footprints in relation to planetary boundaries. Joint EEA/FOEN Report, European Environment Agency (2020).R. J. Scholes, R. Biggs, A biodiversity intactness index. Nature. 434, 45–49 (2005).
26. T. Newbold, L. N. Hudson, A. P. Arnell et al., Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science. 353(6296), 288–91 (2016).
27. K. Sanchez-Ortiz, R. E.Gonzalez, A. De Palma et al., Land-use and related pressures have reduced biotic integrity more on islands than on mainlands, bioRxiv (pre-print). Available at https://doi.org/10.1101/576546.
28. R. Alkemade, M. van Oorschot, L. Miles et al., GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss, Ecosystems. 12(3) 374–390 (2009) R. Alkemade, M. van Oorschot, L. Miles et al., GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss, Ecosystems. 12(3) 374–390 (2009).

Chapter 3

New Zealand's food system – a sector case study

3.1 A global perspective on food systems and environmental sustainability

Food systems are integral to supporting environmental sustainability, yet current global food systems are placing a heavy burden on the environment. From a production perspective, global food production represents the single largest driver of environmental change.[1] Agriculture contributes 9–14% of global greenhouse gas emissions (with total food system activities accounting for 21–37% of greenhouse gases), making food systems a main driver of climate change.[2] Nearly 40% of Earth's land is used to grow food, and food production represents the primary driver of deforestation and biodiversity loss.[3, 4] In our seas, overfishing has led to the collapse of some fish species, with 90% of world fish stocks being fully or over-fished.[5] The way we produce food is also the primary driver of freshwater depletion through agricultural practices such as irrigation and demands nearly 70% of global freshwater use.[6] Excess nitrogen and phosphorus from fertilisers or animal waste can pollute waterways and contributes to global biogeochemical flows beyond a safe operating space.[7–10]

From a consumption perspective, our food choices link to environmental impacts since the foods people eat come with an associated environmental impact. While the magnitude of impact from a specific food can vary depending on the production system, there is a clear hierarchy of environmental impacts across food groups. Plant-based foods consistently incur fewer environmental impacts than animal-based foods across a range of impacts, including greenhouse gas emissions, land use, energy use, acidification and eutrophication potential.[11] Further, research has found that the lowest-impact production of animal-source foods typically still exceeds the environmental impacts of plant-based foods.[12] This suggests that food choice (through demand for production of certain crops/animals) typically has a bigger environmental impact than the way that food was produced.

In short, global food systems are the largest drivers of environmental change and must be transformed if we are to stay within environmental limits.[1] To stay within the food system's fair share of the planetary boundaries, the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems proposed a set of environmental targets specific to food systems (Table 7).[1] Food system environmental targets were developed for five of the planetary boundaries – those most closely related to food systems and for which sufficient data on environmental impacts exist. Globally, the proposed EAT-Lancet targets would mean no new emissions from agriculture, zero net land expansion (particularly into primary habitats), greater than 30% water flows at basin-level, vast reductions in nitrogen and phosphorus pollution and a focus on preserving biodiversity. It should be noted that the EAT-Lancet Commission also produced a set of healthy diet targets but exploring these targets in the New Zealand context is beyond the scope of this report.

The EAT-Lancet Commission explored several global food system scenarios to see if any scenario, now or in the future, could satisfy food system targets – both environmental and healthy-eating targets. The scenarios tested the implementation or business as usual practice of different combinations of dietary shifts, production improvements and reductions in food loss and waste. These measures were included because of their disproportionately high impact on environmental and health outcomes.

Table 7: Environmental targets specific to food systems proposed by EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems.

	Control variable	Boundary (uncertainty range)
Climate change	Greenhouse gas (CH_4 and N_2O emissions)	5 Gt of CO_2 equivalent per year (4.7–5.4)
Nitrogen cycling	Nitrogen application	90 Tg of nitrogen per year (65–90*, 90–130**)
Phosphorus cycling	Phosphorus application	8 Tg of phosphorus per year (6–12*, 8–16**)
Freshwater use	Consumptive water use	2,500 km^3 per year (1,000–4,000)
Biodiversity loss	Extinction rate	Ten extinctions per million species-years (1–80)
Land-system change	Cropland use	13 million km^2 (11–15)

*Lower boundary range if improved production practices and redistribution are not adopted.

**Upper boundary range if improved production practices and redistribution are adopted and 50% of applied nutrients are recycled.

A main finding of the EAT-Lancet report was that it could be possible to feed healthy and sustainable diets to the future global population, but that ambitious action was needed on all three fronts – shifting diets, production improvements and reducing waste. The same conclusion was drawn when assessing environmental impacts only – the focus of this current report. The Commission found that without changing the suite of practices related to the way people consume, produce and waste food globally, food systems of the future are not likely to stay within environmental limits.

3.2 Food systems and the environment in New Zealand

The global perspective on food system impacts taken in the EAT-Lancet is important since food commodities, inputs and other resources move around the world as part of global food systems. However, the five Earth system processes in focus in the EAT-Lancet have most pronounced impacts on human systems at a regional – rather than global – level, with the exception of climate change. Further, the Commission emphasised that the three food system "shifts" (diets, production, waste) needed to achieve sustainable food systems would look different across regions depending on resource allocation, culture, decision-making structures and approaches currently underway to address food system impacts. Thus, a regional analysis of food systems is needed to complement the global perspective. The current report does not endeavour to undertake a comprehensive regional analysis of food systems. It does, however, aim to provide a starting point for linking regional and global fair shares for environmental impacts from food systems.

In New Zealand, agriculture is an economically important industry that utilises the country's abundant natural resources. In particular, dairy and livestock production dominate the sector and are considered important contributors to the national economy. Yet several environmental challenges related to greenhouse gases, land use, biogeochemical flows and biodiversity have been created by food production in the country, as described in Section 1.6.

From a consumption perspective, there are no recent national dietary surveys in New Zealand, making it difficult to understand exactly what New Zealanders are currently eating and how these diets impact the environment. However, adjusted supply data[13] can be used to estimate average dietary patterns across the population. These data illustrate that daily consumption of red meat (beef, pork, lamb) and poultry is over 150g and 80g, or over 1kg and 500g per week, respectively. As discussed above, these foods are associated with relatively high environmental impacts. Other foods that generally have a higher environmental impact, such as nuts, are not major staples to typical New Zealander diets, yet could contribute to healthier diets. Conversely, New Zealanders do consume plenty of foods with low environmental impact, such as sugar or grains, yet excess intake of certain foods from these food groups (e.g., refined grain products, foods high in added sugars) could lead to poorer diet-related health. Overconsumption places additional burdens on the environment through higher demand for natural resources. The growing prevalence of obesity in New Zealand suggests that many adults exceed a healthy energy intake.[14]

Work is already underway to address some of the environmental challenges related to production. These initiatives often focus on improving production practices rather than, for example, exploring changes in land use (e.g., less livestock, more plant-based production), and these are discussed further at the end of this section. Crucially, however, more research is needed to understand how far these changes in production practices, which are distinct from changes in what is produced, will take New Zealand towards reaching its environmental goals including its fair shares of the planetary boundaries. Remembering that globally, only the combination of production improvements, dietary shifts and reductions in food loss and waste will reduce the environmental impacts of food systems within safe thresholds, it will be important to consider what other measures beyond production improvements might also be needed in New Zealand.

Limiting food system impacts to the fair shares proposed in this section will be challenging if not accompanied by global shifts towards more environmentally friendly food production (which would affect the environmental impact of foods imported and consumed in New Zealand) and consumption (which would impact demand for New Zealand food production).

3.3 Fair shares of environmental impact from food systems in New Zealand

The starting point to propose fair shares of environmental impacts from New Zealand food systems was the EAT-Lancet global food-system targets. As described in the panel below, the approach of the EAT-Lancet Commission to setting food-system boundaries differed from the approach used to set the original planetary boundaries. The different approach of the Commission takes into account the unique challenges and structure of the food system. While this does raise a number of inconsistencies between approaches used to set global or sector-specific allocations, reconciling these differences is beyond the scope of this report.

The method of translation from global food system to national fair shares, however, is consistent with the approach taken elsewhere in this report. The EAT-Lancet targets have been adapted to national allocations using an equal-per capita approach. This means that the global food system targets are divided equally by the world population. The allocations can then be scaled to a national level by multiplying by a country's population (or projected population for future years). The global, per capita and New Zealand food-system boundaries are shown in Table 8. Allocations are given for 2010 (baseline year) and 2050, with differences reflecting changes in population at the global and national level.

We note that the EAT-Lancet nomenclature of "targets" aligns with the concept of "guardrails" described previously. To align with the nomenclature used in this report, we henceforth refer to the adapted EAT-Lancet targets to the New Zealand context as allocations or fair shares. We also note that in this report, we translate four of the EAT-Lancet food system targets – those for climate change, biogeochemical flows (both nitrogen and phosphorus cycling), freshwater use and land-system change. Determining a fair share of biodiversity-loss in New Zealand arising from food system activity will require further work.

As discussed previously, there is no "right" way to divide these fair shares among regions, sectors or individuals. There are a number of ways to translate fair shares based on differing underlying assumptions about, for example, natural resource availability, equality, historical environmental impact and so on. This holds true for adaptation of food system allocations as well.

For example, trade could be an important consideration when determining national food-system fair shares. New Zealand exports a large share of the food it produces (up to 90%[15]), meaning the New Zealand food system feeds more than just its population, but individuals around the world. On one hand, this could point to the justification for New Zealand to get a larger share of the global boundary. On the other hand, it could be argued that many of the foods that New Zealand produces, such as milk, beef and lamb, are environmentally intensive foods to produce, and this type of production does not warrant a higher allocation for New Zealand than for other countries (based on population).

Table 8: Fair shares of food system environmental impacts: global EAT-Lancet targets, per capita allocations and New Zealand allocations determined using the per capita approach.

	GHG emissions*	Cropland use**	Blue-water use	Nitrogen application	Phosphorus application	Biodiversity
EAT-Lancet global targets	**($GtCO_2$-eq/yr)**	**(million km^2)**	**(km^3/yr)**	**(Tg N/yr)**	**(Tg P/yr)**	**(extinction/million species-years)**
Target	5	13	2,500	90	8	
Per capita allocation	**(tCO_2-eq/yr)**	**(km^2)**	**(m^3/yr)**	**(kg N/yr)**	**(kg P/yr)**	
Allocation	0.7 (2010) 0.5 (2050)	0.002 (2010) 0.001 (2050)	360 (2010) 270 (2050)	13 (2010) 10 (2050)	1.2 (2010) 0.9 (2050)	More work needed
New Zealand allocation	**($MtCO_2$-eq/yr)**	**(km^2)**	**(km^3/yr)**	**(Tg N/yr)**	**(Tg P/yr)**	
Allocation	3.17 (2010) 3.23 (2050)	8,250 (2010) 8,405 (2050)	1.59 (2010) 1.62 (2050)	0.06 (2010) 0.06 (2050)	0.005 (2010) 0.005 (2050)	More work needed

*Includes methane and nitrous oxide, and only minor CO_2 emissions from biofuel burning.
** Includes cropland only, not e.g., pastures.

Additionally, the Earth system processes explored here, with the exception of greenhouse gas emissions, are sensitive to regional variations. Thus, there are limitations to developing fair shares based on equal per capita allocations of environmental impact, which are detailed further in the discussion of this chapter. Despite these limitations, alternative control variables were not developed for this analysis.

The New Zealand fair shares are based on the global food system boundaries. If different control variables were used at the country level, then the results might no longer be comparable to the food system allocations presented above. However, we stress that the allocations proposed here are just one example of national food-system targets. Thus, this report provides a starting point for development of more holistic and context-specific allocations.

Methods to determine 'fair shares' of overall and food-system environmental impacts for New Zealand

This report has engaged parallel efforts to estimate fair shares of environmental impacts, following both an Earth-system approach and a food-system approach. In both efforts, the method to undertake the primary task of this report – translation of a global safe operating space to a fair share for New Zealand – was consistent. That is, the equal-per capita approach was used to determine both the overall and food-system environmental impacts for New Zealand.

However, these efforts were borne of two frameworks that varied in their underlying assumptions. The overall fair shares for New Zealand took the planetary boundary framework as the starting point, while the food system fair shares took the EAT-Lancet Commission framework for global food system targets as the starting point. As illustrated in Table 9, this has resulted in different characterisations of fair shares in terms of, for example, control variables or conflicting allocations. In this section we endeavour to clarify the similarities and differences of these two approaches.

Table 9: Summary of the planetary boundary (PB) and food-system allocations in comparable units.

	Planetary boundary		Planetary boundary national allocation		EAT-Lancet targets		NZ food-system allocation
Boundary	**Control variable**	**Global limit**	**Equal per capita**	**Equal per area**	**Control variable**	**Global limit**	**Equal per capita**
Climate change	CO_2 emission (+1.5°C)	420–840 $GtCO_2$*	3.1–6.3 million tCO_2	--	CO_2-eq emission (CH_4, N_2O)	5 $GtCO_2$-eq	3.2 million tCO_2/yr
	CO_2 emission (+2°C)	1,170–2,030 $GtCO_2$*	8.7–15.1 tCO_2	--			
Land-use change	Cropland conversion	15%	--	3.95 million ha	Cropland use	1,300 million ha	840,500 ha
Freshwater use	Blue-water use	4 trillion m^3/yr	2.51 billion m^3/yr	--	Consumptive water use	2.5 trillion m^3/yr	1.6 billion m^3
Biogeo-chemical flows	N applications	62 Tg N/yr	38.8 million kg N/yr	25.6 million kg N/yr	Nitrogen application	90 Tg N/yr	60 million kg/yr
	P applications	6.2 Tg P/yr	3.8 million kg P/yr	2.56 million kg P/yr	Phosphorus application	8 Tg N/yr	5 million kg/yr

3.4 Quantitative comparison of New Zealand's food production and consumption environmental impacts to proposed allocations

The EAT-Lancet data were used to estimate the baseline impact of New Zealand food production and consumption on methane and nitrous oxide, cropland use, blue-water use, nitrogen application and phosphorus application. Details about the EAT-Lancet food systems model, data sources and analysis are presented elsewhere.[1,16] The baseline year for this food system analysis is 2010, consistent with the EAT-Lancet analysis.

The two approaches are similar in that the EAT-Lancet Commission took the original planetary boundary science as the starting point for defining a global safe operating space for food systems. However, taking a sector-specific approach to defining a safe operating space poses additional challenges. The question is not simply "What share of the global safe operating space should be allocated to food systems?" Rather, the question becomes, "What is a safe operating space for food systems that allows sustainable food to be produced for a growing global population expected to reach nearly 10 billion people by 2050?" Thus, additional criteria need to be considered when developing the safe operating space.

The EAT-Lancet report also had several core assumptions that differed from the original planetary boundary science. First, when defining the climate change boundary, the Commission focused on methane and nitrous oxide as the primary control variables. The reasoning was twofold. One, the Commission assumed that the world would have delivered on the Paris Climate Accord, meaning CO_2 emissions would reach zero by 2050. What remains after the entire food system is decarbonised is methane and nitrous oxide. The Commission concluded that a sustainable food system feeding 10 billion people would still emit up to 5 $GtCO_2$-eq. This corresponds to an assessment of the residual fluxes of non-CO_2 gases from agriculture that very likely will always be associated with food production, i.e., in short, to feed 10 billion people will per necessity come at a certain "price", in terms of water, land, nutrients, energy. One such minimum price is 5 $GtCO_2$-eq of climate forcing. And two, while CO_2 is the most important greenhouse gas from a physics perspective (explaining up to 70% of overall warming in the atmosphere), in a planetary boundary perspective, other greenhouse gases become important, particularly when narrowing in on specific sectors. The agricultural sector is a disproportionately large source of the biogenic greenhouse gases methane and nitrous oxide, associated with livestock and soil microbial transformation of nitrogen sources into nitrous oxide.

Second, the cropland allocations differ in their focus between approaches. The planetary boundary allocation is based on a total amount of land area that can be converted to cropland (15%), whereas the food-system allocation is based on no net land conversion to agricultural land. The EAT-Lancet Commission arrived at this premise through adoption of the Half Earth strategy (i.e., keep 50% of Earth's remaining land as intact ecosystems) to account for land-system change and biodiversity loss. This has led to a very different outcome. New Zealand has a very low percentage of land area currently considered cropland, approximately 645,000 ha, or 2.4% of its land area in 2017. Therefore, if held to a no net conversion criteria, it follows that the food-system allocation has a much lower threshold (840,500 ha) compared to the PB allocation (3.95 million ha).

Third, the EAT-Lancet report includes elements of biogeochemical flows not found in the original planetary boundary work. The EAT-Lancet proposed a stepwise approach to determining the boundary for nitrogen and phosphorus, reflected in the two different ranges proposed for global nitrogen and phosphorus application. The lower range aligns with the original Earth-system-defined planetary boundary. In the New Zealand context, this may mean that the country already exceeds this threshold necessitating lower nutrient inputs to soils. The second, higher range assumes management practices where nutrients are recycled, thus allowing for a higher application of nutrients, providing that nutrient loops are closed.

Finally, however, the freshwater allocations should be highlighted as a point of alignment. The food-system approach considers food production as fundamental to human well-being, with priority on closing yield gaps in many parts of the world. Therefore, the agriculture sector is allowed a larger future allocation of the overall planetary boundary. In this context, the food-system fair share (1.62 billion m^3/yr) fits within the national allocation (2.49 billion m^3/yr).

The differences between these two approaches described above highlight points of tension between global and sector-specific development of safe operating spaces. While it is beyond the scope of this report to resolve these tensions, it raises important future research areas.

Projected environmental impacts in 2050 are based on the "business as usual" EAT-Lancet scenario, outlined further elsewhere.[16] This means that current environmental impacts were paired to future projections of food demand. For this analysis, food demand was estimated along the SSP2 socioeconomic pathway, which assumes a moderate socio-economic development pathway. Further details are presented in Springmann et al.[16]

Table 10 presents the comparison of the environmental impacts of New Zealand food production and consumption against the New Zealand food system allocations proposed above. The discussion below highlights where the New Zealand food system is exceeding the proposed fair shares and further underscores the need for additional work to set national food-system fair shares.

Table 10: Comparison of the New Zealand food-system fair shares to baseline (2010) and projected (2050) environmental impacts from food consumption and production.

	GHG emissions ($MtCO_2$-eq/yr)	Cropland use (km^2)	Blue-water use (km^3/yr)	Nitrogen application (Tg N/yr)	Phosphorus application (Tg P/yr)
New Zealand allocation in 2010 New Zealand allocation in 2050	3.2 3.2	8,250 8,405	1.6 1.6	0.06 0.06	0.005 0.005
Production-based impacts in 2010 Production-based impacts in 2050	39.0 55.4	4,170 6,200	0.5 0.9	0.03 0.05	0.005 0.008
Consumption-based impacts in 2010 Consumption-based impacts in 2050	4.2 6.6	2,610 4,050	0.3 0.6	0.02 0.03	0.003 0.005

3.4.1 Production-based impacts

Analysis of food-production impacts (to farm gate) assessed all foods produced in New Zealand, regardless of whether the final food product was consumed domestically or exported. The section below presents the complementary consumption-based approach to environmental impacts of food systems, meaning that all food consumed in New Zealand, regardless of origin, was considered. Here, consumption estimates have been adjusted for waste, meaning only food consumed (and not food wasted), is included. Figure 22 shows the production- and consumption-based impacts for each environmental indicator in 2010 and 2050.

From a production perspective New Zealand food production generated over ten times (39 $MtCO_2$-eq) the sustainable level of CO_2-eq in 2010. By 2050, this would rise to 55 $MtCO_2$-eq, well beyond the proposed fair share. Dairy, lamb and beef production accounted for the largest share of CO_2-eq (35%, 34%, 30% of total CO_2-eq, respectively). This is unsurprising given the dominance of these production systems in New Zealand agriculture.

Phosphorus application related to food produced in New Zealand in 2010 reached the sustainable fair share of 0.005 Tg P yr^{-1}. By 2050, it is projected to overshoot the fair share with an estimated 0.008 Tg P yr^{-1}. In our model, vegetable production and milk production accounted for the largest share of phosphorus application.

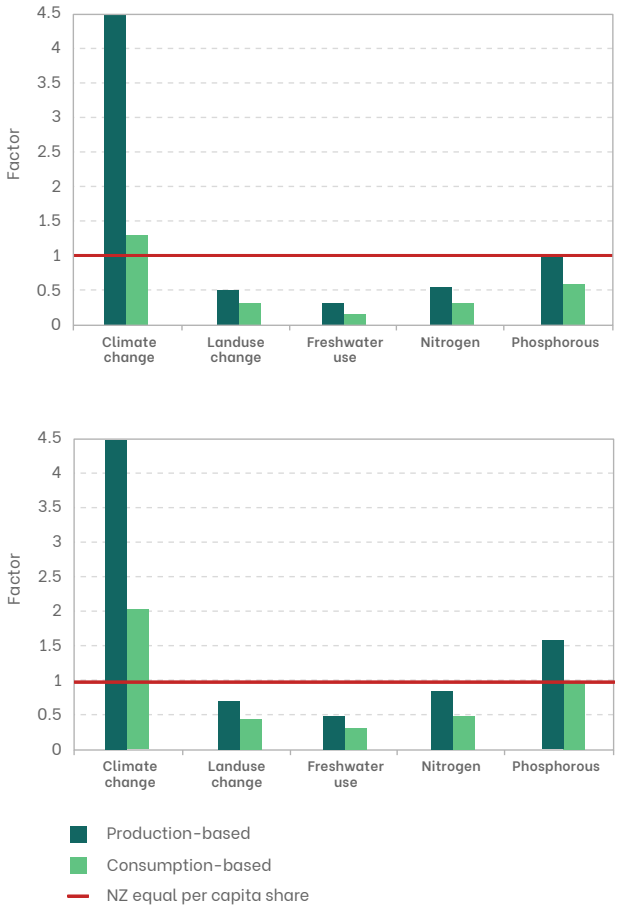
The cropland use, blue-water use and nitrogen application associated with food production in New Zealand were all within the proposed fair shares. However, there are several caveats when interpreting these results, outlined in the discussion below.

3.4.2 Consumption-based impacts

In the baseline year of 2010, New Zealand's food consumption produced approximately 1 million tonnes more CO_2-eq (4.2 $MtCO_2$-eq) than would be considered sustainable using the per capita allocation approach (3.17 $MtCO_2$-eq). Beef and lamb accounted for the most consumption-based CO_2-eq (35% and 45% of total CO_2-eq, respectively). This is unsurprising, given both the high environmental impact of these foods and the high consumption of red meat in New Zealand. By 2050, New Zealand food consumption is projected to twice exceed its fair share.

We again stress that the emissions target of the EAT-Lancet focuses on methane and nitrous oxide. To estimate all greenhouse gas emissions resulting from food consumption in New Zealand, we used data from the EAT-Lancet model to conduct a sensitivity analysis. This analysis used LCA data and included carbon emissions in addition to methane and nitrous oxide. Based on this sensitivity analysis, we found that, unsurprisingly the GHG emissions of New Zealand food consumption are higher than the estimates presented in Table 10. In 2010, total consumption-related food emissions contributed 14 million tonnes of CO_2-eq, projected to rise to 22 million tonnes CO_2-eq in 2050.

Figure 22: Normalised production-based and consumption-based environmental impacts in 2010 (top) and 2050 (bottom) compared to the proposed food-system allocations for New Zealand indicated by the horizontal red line. Note that the production-based impacts on climate change in both 2010 and 2050 exceed the axis limits.



For phosphorus application, New Zealand consumption was within the sustainable fair share for the baseline year and 2030, but reached the proposed allocation (0.005 Tg P/year) by 2050. Consumption of vegetable oils, wheat and sugar accounted for the most phosphorus application.

For cropland use, blue-water use and nitrogen application, New Zealand's food consumption impacts were within the sustainable fair share for all years. However, we again note the caveats (discussed below) when interpreting these results.

3.4.3 Discussion of results

Our analysis indicates that New Zealand currently or will in the future transgress the fair shares of methane and nitrous oxide emissions and phosphorus application related to food systems. Below we discuss these findings and compare to similar analysis undertaken in New Zealand. We also underscore the need for work to further develop these fair shares so that they appropriately measure the environmental impacts borne of the New Zealand context.

From a production perspective, New Zealand exceeded its fair share allocations of methane and nitrous oxide. The majority of greenhouse gases were produced through dairy, beef and lamb systems, the dominant food production systems in New Zealand. This suggests that both the type of production (e.g., livestock versus other food production) and production practices (e.g., climate-friendly production practices) could be reviewed to understand how New Zealand can best remain within its fair share. It is beyond the scope of this chapter to discuss national decisions about how emissions reductions are to be balanced across sectors.

Our emissions estimate can be compared with existing estimates. The Ministry for the Environment (MfE) publishes historical and projected greenhouse emissions.[17] Based on the MfE analysis, the agricultural sector was estimated to produce about 37 Mt methane and nitrous oxide in 2010, the baseline year presented in this analysis. This is largely aligned with our estimate of 39 Mt methane and nitrous oxide emissions. In 2050, however, MfE projected that the agricultural sector would decrease these emissions to about 33 Mt methane and nitrous oxide, while our analysis projected emissions to rise to 55 Mt. This could be due to many methodological differences between the approaches. For example, the MfE estimate considers implementation of policy measures prior, but not subsequent to, 2019 whereas the EAT-Lancet did not consider implementation of specific national policies. Additionally, the MfE scenarios used for this estimate based future agricultural emissions on projections of agricultural production,[17] while the EAT-Lancet scenarios estimated these emissions based on future food demand.[16]

From a consumption perspective, New Zealand also exceeds its fair share of methane and nitrous oxide, but to a much smaller extent than found in the production-oriented analysis. This could be due to the fact that methane and nitrous oxide – the control variables used here – dominate New Zealand food production emissions, but CO_2 emissions play a much greater role from a consumption perspective.

We estimated that *all* greenhouse gas emissions (i.e. all CO2-eq, including carbon dioxide) from food consumption in New Zealand totalled 14 $MtCO_2$-eq/yr. A recently published analysis found that New Zealand diets produce 9.2 $MtCO_2$-eq/yr.[18] There are many differences in the methods of the two approaches that could account for the different estimations. For example, the Drew et al. analysis[18] estimated yearly emissions of adults 15 years and older, while our analysis is based on the total population in New Zealand. Drew and colleagues in fact state that "these numbers are certainly underestimates given that they do not include emissions associated with the diets of the nearly 1 million New Zealanders who are <15 years of age". Additionally, in their analysis, consumption data was determined through national nutrition surveys, while the EAT-Lancet Commission estimated consumption through adjusted supply data. Differences could arise due to, for

example, underreporting of consumption in dietary surveys. Further, different LCA databases were used, impacting the estimation of emissions for specific food items. This is not an exhaustive list of differences yet provides insights into the discrepancy between estimates.

To reduce consumption-based greenhouse gas emission impacts within the per capita allocations, our analysis indicates that a shift in dietary patterns away from major sources of methane and nitrous oxide (e.g., red meat) and towards other plant-based alternatives would be needed. This is consistent with previous research.[18] However, it is possible that a combination of shifts in dietary patterns, along with changes in production and reductions in food loss and waste are needed. This is an important area of further research.

Our analysis also indicated that New Zealand currently reached the fair share allocation for phosphorus and would exceed the allocation by 2050, from a production perspective. We note that this might be an underestimation, since the EAT-Lancet model used regional averages. National data indicate that 0.14 Tg of phosphorus was applied in 2010 (compared to our estimate of 0.005), meaning New Zealand would far exceed its fair share.[19] Thus, use of national data can help improve the accuracy of production impacts. Further, vegetable production and milk production accounted for the largest share of phosphorus application. This finding is not aligned with national data that identified sheep and beef and dairy farms as the farming systems accounting for most phosphorus fertiliser. This could be due to fertiliser practices in New Zealand that differ from global averages used in the EAT-Lancet analysis.

From a consumption perspective, we projected that New Zealand would reach its fair share of phosphorus application by 2050. Our analysis suggests that a reduction in vegetable oils, wheat and sugar could maintain consumption within the phosphorus fair share. Again, noting the lack of current dietary surveys, it is difficult to determine how these commodities are being consumed in the diet (e.g., wheat as a whole or highly-refined grain product), and these dietary shifts should be considered in the context of other factors, such as achievement of nutritious diets and proper energy balance (e.g., reducing energy-dense discretionary foods).

As noted throughout the report, there are certain limitations of translating global fair shares to national fair shares. Several limitations arise in the food system analysis, discussed below, which signal important areas of future research.

The cropland allocation could benefit from a broader consideration of land-use in New Zealand. For example, while only about 2% of New Zealand's land is cropland, nearly 40% is pastureland – a key resource use for New Zealand's meat production. Thus, a multi-dimensional allocation for different agricultural land uses could be developed. Local land use targets may differ depending on context, but should account for factors such as the need to ensure appropriate conservation of biodiversity.

When assessing blue-water use, the EAT-Lancet Commission stressed the need for assessment at the basin level, since local hydrological dynamics impact allowable withdrawals and consumption. A water allocation could be set so that sufficient water flow is maintained within the various water basins in New Zealand. In addition, the accounting of blue-water use in the EAT-Lancet report does not include direct withdrawals for animals (only the indirect blue-water impact of animals via feed production).

Finally, when assessing nitrogen, it is important to consider that the nitrogen fair share reflects only nitrogen application rates. However, there are other sources of nitrogen (e.g., urine patches from livestock) that can contribute to environmental challenges, such as eutrophication. In the global EAT-Lancet analysis, a sensitivity analysis was run to account for all sources of nitrogen inputs and offsets, i.e., surplus reactive nitrogen. This same analysis was done for New Zealand. When accounting for all inputs and offsets of nitrogen, New Zealand food production in 2010 resulted in 0.068 Tg of nitrogen inputs to soils in 2010. In 2050, this is projected to be 0.123 TgN/yr, twice exceeding the allocation. Further, our figures might be an underestimation given that application in New Zealand was estimated from average regional applications. National statistics indicate that 0.341 Tg of nitrogen was applied in New Zealand in 2010, far beyond the fair share.[19] Because New Zealand has other significant inputs of nitrogen beyond fertilisers, this highlights that further work is needed to determine an appropriate nitrogen boundary for New Zealand and that use of local data can provide a more accurate estimate of nitrogen application.

The benefits and limitations of a global-national translation of the EAT-Lancet environmental targets has been discussed in a recent analysis from Sweden.[20] The authors used the same equal-per capita approach as was used in this report to translate the global EAT-Lancet environmental targets to the Swedish context. The authors then benchmarked the environmental impacts of current Swedish diets to these country-level targets. The analysis also compared existing national environmental targets to the global EAT-Lancet targets and suggested additional indicators to appropriately capture aspects of the local context. A similar exercise could be undertaken in New Zealand.

3.5 Looking ahead: sustainable food systems in New Zealand

This analysis has highlighted the environmental challenges New Zealand might face in the future regarding food systems. However, our analysis was based on a business-as-usual scenario, and efforts to reduce environmental impacts of food systems could result in a more positive assessment.

Many such efforts are indeed already underway. On the production side, for example, research and innovation funds support partnerships, technologies and production practices to address the climate challenges of agriculture. Innovative initiatives underway include mitigation of agricultural methane emissions through seaweed aquaculture or low-methane animal breeds.[21] Research on climate-friendly production is also being funded to explore methods to, for example, increase soil carbon sequestration or reduce nitrous oxide emissions.[22] To stop the decline of freshwater resources, water quality measures, such as the National Policy Statement for Freshwater Management or the objectives and instruments of the government's Essential Freshwater programme, have been or are being developed. Biodiversity strategies at national[23] and local[24] levels are being developed to protect and promote the unique flora and fauna of the country. Biodiversity in New Zealand seas has long been promoted through the Quota Management System,[25] used to promote the sustainability of New Zealand's fish stocks and rebuild those stocks that are currently overfished.[26] In this way, New Zealand's agricultural sector has a significant opportunity to meet (and even drive) both supply and demand for healthy and sustainable food.

It is crucial to consider, however, that food systems are much more than the environmental impact of what we produce, consume and waste. Indeed, they are linked to nearly all aspects of well-being and sustainable development, as food impacts our health, culture, economy and livelihoods. While we have focused on environmental impacts in this report, we support the many other researchers who have called for a more holistic evaluation of food system impacts moving forward.[27–29]

Taking a systems-based approach to food-system impacts allows us to explore the many linkages between production, consumption and the other parts of the food system, such as the people, activities and elements that are related to food as it makes it way from farm to fork (or bin). It allows us to focus on the impacts and trade-offs across a broader set of systems, such as health, economic and social systems.[30] Crucially, it allows us to identify synergies, for example, where food systems support a more sustainable planet, healthier people and greater well-being of societies.

Existing guidelines and frameworks in New Zealand can be built upon to illustrate how sustainable food systems contribute to a broader set of well-being targets, such as the Living Standards Framework (LSF) proposed by the New Zealand Treasury.[31] For example, the LSF highlights that a secure income and good jobs are integral to the well-being of New Zealanders. Agriculture, forestry and fishing provide the main source of income for 120,000 New Zealanders,[32] and the food and beverage sector employs nearly 100,000 New Zealanders.[33] However, some of these jobs are at risk due to climate change. For example, increases in temperature, flooding, droughts or erosion can threaten the agricultural sector, although not all impacts of climate change may be negative.[34]

The LSF also underscores the need for good health. Healthy diets not only contribute to a state of good health but can also contribute environmental benefits. Yet in New Zealand, unhealthy diets were the second leading risk factor of poor health in 2017.[35] Poor diets are contributing to unhealthy weights and obesity – one in three adults and one in eight children are obese – and other non-communicable diseases such as cardiovascular disease and diabetes.[36] A recent analysis explored a range of dietary shifts in line with health and/or sustainability recommendations, for example, eating in line with the New Zealand dietary guidelines or reducing/replacing all animal-source foods. They found that these shifts could result in health savings of 1–1.5 million quality adjusted life years and NZ$14–20 billion health system cost savings while also reducing emissions by up to 2.78 kg per day in a typical diet.[18]

Other frameworks, such as Ngā Tūtohu Aotearoa – Indicators Aotearoa,[37] further illustrate the connections between food and well-being. For example, cultural well-being can be promoted through intergenerational transfer of knowledge on sustainable food production or preparation. These examples demonstrate that policies related to food could account for the social, economic, and environmental impacts of foods to ensure that measures support, rather than undermine, each other.

Inevitably, there will be trade-offs that result from competing priorities within the food system. For example, agriculture is part of the backbone of the New Zealand economy, particularly as an export sector. Up to 90% of the food produced is exported, with food and agricultural products totalling nearly NZ$40 billion in export earnings (excluding forestry, year ending June 2019).[15] Dairy, meat and wool are the largest export earners at NZ$18, 10 and 7 billion, respectively. However, these industries also account for the largest share of environmental impact from food production. Solutions could seek to minimise trade-offs and support those who might lose out in food systems change.

There is potential for policies to deliver on multiple domains of well-being by identifying actions that maximise synergies across goals. Because these trade-offs require normative decisions, inclusive multi-stakeholder dialogues could be used to make sure that all stakeholders and individuals have their say on the future of New Zealand's food system.

References

1. W. Willett, J. Rockström, B. Loken et al., Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet*. 393(10170), 447–92.
2. IPCC, Special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (2019).
3. World Bank, World Bank Open Data, (2019).
4. T. Newbold, L. N. Hudson, A. P. Arnell et al., Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science*. 353(6296), 288–91 (2016).
5. FAO, The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all, (2016).
6. Comprehensive Assessment of Water Management in Agriculture, Water for food, water for life: a comprehensive assessment of water management in agriculture. Earthscan and Colombo: International Water Management Institute (2007).
7. D. Cordell, S. White, Life's bottleneck: sustaining the world's phosphorus for a food secure future. *Annual Review of Environment and Resources*. 39, 161–88 (2014).
8. R. J. Diaz, R. Rosenberg, Spreading dead zones and consequences for marine ecosystems. *Science*. 321(5891), 926–9 (2008).
9. 9. G. P. Robertson, P. M. Vitousek, Nitrogen in agriculture: balancing the cost of an essential resource. *Annual review of environment and resources*. 34, 97-125 (2009).
10. J. Rockström, W. Steffen, K. Noone et al., Planetary boundaries: exploring the safe operating space for humanity. *Ecol Soc*. 14(2) (2009).
11. M. Clark, M. Springmann, J. Hill, D. Tilman, Multiple health and environmental impacts of foods. *PNAS* (2019).
12. J. Poore, T. Nemecek, Reducing food's environmental impacts through producers and consumers. *Science*. 360(6392), 987–92 (2018).
13. M. Springmann, Supplementary data to EAT-Lancet Commission on healthy diets from sustainable food systems (2019).
14. Ministry of Health, Annual Data Explorer 2017/18: New Zealand Health Survey (2019).
15. MPI, Situation and outlook for primary industries. Wellington, NZ: Ministry for Primary Industries (2019).
16. M. Springmann, M. Clark, D. Mason-D'Croz et al., Options for keeping the food system within environmental limits. *Nature*. 1 (2018).
17. Ministry for the Environment, New Zealand's projected greenhouse gas emissions. (2020). Available at https://www.mfe.govt.nz/climate-change/emissions-reduction-targets/projected-emissions.
18. J. Drew, C. Cleghorn, A. Macmillan, A. Mizdrak, Healthy and Climate-Friendly Eating Patterns in the New Zealand Context. *Environ. Health Perspect*. 128, 17007 (2020).
19. Fertilizer Association of New Zealand. Fertilizer use in New Zealand (2018). Available at http://www.fertiliser.org.nz/Site/about/fertiliser_use_in_nz.aspx#nitrogen-use).
20. E. Moberg, H. Karlsson Potter, A. Wood, P.-A. Hansson, E. Röös, Benchmarking the Swedish Diet Relative to Global and National Environmental Targets—Identification of Indicator Limitations and Data Gaps. *Sustainability*. 12, 1407 (2020).
21. MPI, Sustainable Food & Fibre Futures (2019). Available at: https://sff-futures.mpi.govt.nz/funding-and-programmes/sustainable-food-and-fibre-futures/.
22. MPI, Global Partnerships in Livestock Emissions Research (2017). Available at https://www.mpi.govt.nz/funding-and-programmes/farming/global-partnerships-in-livestock-emissions-research/.
23. New Zealand Government, Te Koiroa o te Koiora. Wellington, NZ, (2019).
24. Greater Wellington Regional Council, Wellington Regional Biodiversity Framework (2019). Available at https://haveyoursay.gw.govt.nz/wrbf.
25. 25. Fisheries New Zealand, Quota Management System (2019). Available at https://www.mpi.govt.nz/law-and-policy/legal-overviews/fisheries/quota-management-system/.
26. 26. MPI, Fish stock status (2019). Available at https://www.mpi.govt.nz/growing-and-harvesting/fisheries/fisheries-management/fish-stock-status/.
27. A. Chaudhary, D. Gustafson, A. Mathys, Multi-indicator sustainability assessment of global food systems. *Nature communications*. 9(1), 848 (2018).
28. D. Gustafson, A. Gutman, W. Leet, A. Drewnowski, J. C. Fanzo, J. Ingram, Seven food system metrics of sustainable nutrition security. *Sustainability*. 8(196) (2016).
29. J. C. Fanzo, B. Cogill, F. Mattei, Metrics of Sustainable Diets and Food Systems. *Bioversity International* (2012).
30. K. Parsons, C. Hawkes, Connecting food systems for co-benefits: how can food systems combine diet-related health with environmental and economic policy goals? European Observatory on Health Systems and Policies (2018).
31. New Zealand Treasury, The Treasury Approach to the Living Standards Framework. Wellington, NZ: New Zealand Government (2018).
32. Stats NZ, New Zealand business demography statistics (2018).
33. MBIE, Beyond commodities: manufacturing into the future. Wellington, NZ: New Zealand Government (2018).
34. Climate Change Adaptation Technical Working Group, Adapting to climate change in New Zealand (2017).
35. IHME, Health data – New Zealand (2019). Available at http://www.healthdata.org/new-zealand.
36. J. D. Stanaway, Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*. 392(10159), 1923–94 (2018).
37. Stats NZ, Ngā Tūtohu Aotearoa – Indicators Aotearoa New Zealand (2019). Available at https://www.stats.govt.nz/indicators-and-snapshots/indicators-aotearoa-new-zealand-nga-tutohu-aotearoa/

Chapter 4

Policy

4.1 Planetary boundaries and international policy

The international policy system for environmental governance has emerged in a piecemeal way in response to specific problems. This makes it challenging to adopt a systems approach to policies related to the future risks flagged by the planetary boundaries. Global policy frameworks related to specific planetary boundaries exist and deal with some of their interactions, for example, around climate, land use and biodiversity (see Figure 23). These are potentially effective but incentives to comply are weak, and sanctions are largely missing. Indeed, in recent years, international policy has shifted from a system based on rules and penalties for transgression towards a system based on goals with weak or no penalties for transgression.[1] The implications of this move for collective action towards protecting the global commons and navigating towards a safe operating space for humanity are unclear.

A well-documented successful example of global policy with particular resonance for New Zealand is the Montreal Protocol, established in 1987. The protocol outlawed ozone-depleting substances to the point that the ozone layer has stabilised and is expected to recover. Several international conventions cover novel entities, an issue included in the planetary boundaries framework but with no globally quantified boundary. For example, there are global agreements to restrict environmental harms from nuclear material, chemical weapons and marine pollution, although with 100,000 synthetic chemicals in circulation, only a handful are explicitly addressed within these conventions.

Of all boundaries, only the biogeochemical flows boundary relating to nitrogen and phosphorus use has no existing global framework. There are some international regulations for nitrogen and phosphorus, e.g., at the EU level and for the Baltic Sea (Helcom – the Baltic Marine Environment Protection Commission), and the effects of nitrogen flows are increasingly explicit in implementation of climate and biodiversity policy. In October 2019, 197 scientists wrote an open letter to the United Nations to voice concern regarding the current lack of policy coherence at local, regional and global scales. The group supports the new UN goal to halve nitrogen waste from all sources by 2030.

In 2020, there are opportunities to improve coherence between international and national policies. With the renewal of the strategic plan for the Convention on Biological Diversity, clear opportunities exist to strengthen targets related to biodiversity. Within the Paris Agreement, countries are obliged to increase ambition on climate action through the "ratchet mechanism". And the UN will continue a process to improve management of the oceans.

The planetary boundaries framework is the most coherent framework to date for a systemic view of Earth's long-term stability in support of the resilience of the world's social ecological systems. It is not an internationally adopted framework for sustainable development, but it did inform discussions relating to the creation of the Sustainable Development Goals. For example, the UN Secretary-General's report Resilient People Resilient Planet (2012) states, "We are reaching, and increasingly overstepping, planetary boundaries".[2] The report recommended that "Governments and the scientific community should take practical steps [...] to strengthen the interface between policy and science. This should include the preparation of regular assessments and digests of the science around such concepts as 'planetary boundaries', 'tipping points' and 'environmental thresholds' in the context of sustainable development".[2] The planetary boundaries concept is also included in assessment reports of intergovernmental agencies, for example the 2011 OECD report Towards Green Growth[3] and UNEP's 2012 Global Environmental Outlook 5.[4]

The European Union's 7th Environment Action Programme, Living Well, Within the Limits of Our Planet, guides the environmental policy agenda up to 2020. It contains many direct references to the planetary boundaries, as well as to the Agenda 2030 Sustainable Development Goals (SDGs). Supporting this action programme, the European Environment Agency has commissioned studies on the operationalisation of the planetary boundaries at EU level.[5] More recently, in 2020, the European Environment Agency published Is Europe Living Within the Limits of Our Planet?[6] The aim of the report was to explore how the use of different allocation principles influences the definition of European limits for select planetary boundaries.

European nations have been particularly active in advancing discussions on the relationship between planetary boundaries and global sustainable development. In 2013, the environment ministries of Finland, Sweden, Norway and Denmark, with the United Nations Environment Programme and the Stockholm Resilience Centre organised an international workshop, Planetary Boundaries and Environmental Tipping Points: What Do They Mean for Sustainable Development and the Global Agenda? To some extent, the workshop's key recommendation, to tie the safe and just operating space into the post-2015/SDG political processes, has been taken up. Climate change, biodiversity loss, freshwater use and land-use change are the focus of dedicated SDGs and the other boundaries are also included in some of the targets and indicators.

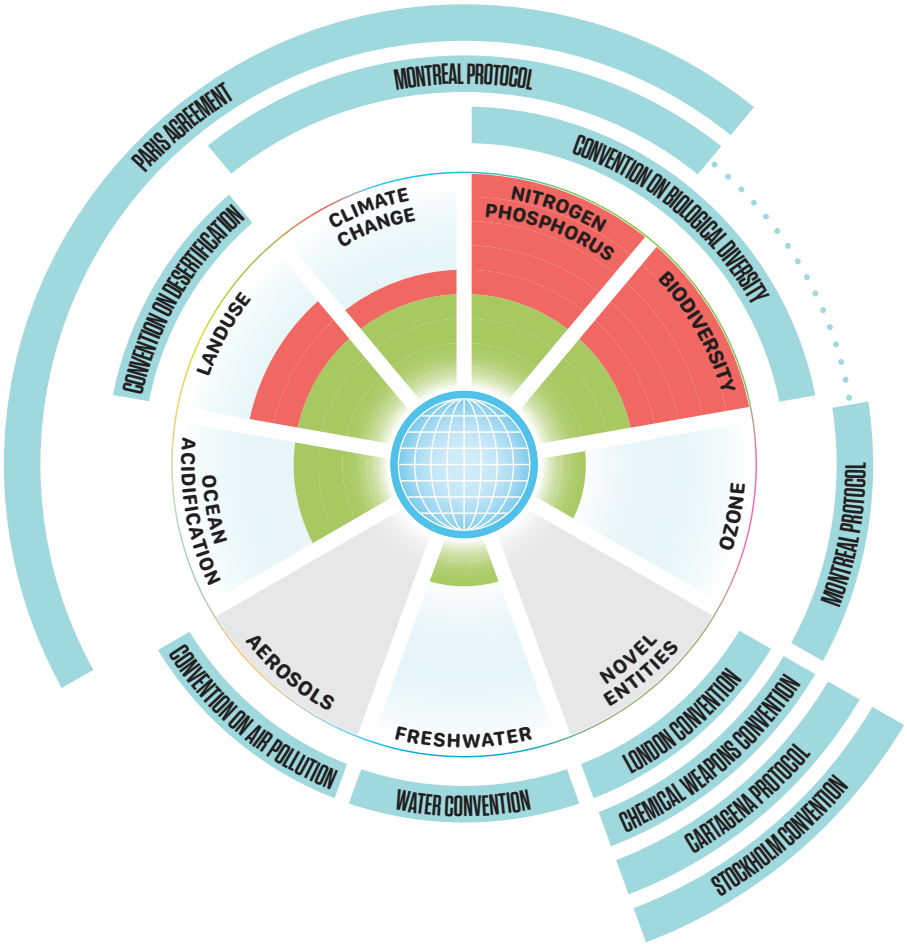
The network of European Environment and Sustainable Development Advisory Councils (EEAC) convened a workshop in Brussels in 2014, Safe Operating Space: Current State of Debate and Considerations for National Policies.[7] It paid special attention to the issue of implementing the framework with EU and national policies, concluding that the planetary "safe operating space" framework gives a benchmark for formulating policy targets and could therefore be used to assess the level of transitions needed at national and European levels.

In 2017, the Potsdam Institute, Stockholm Resilience Centre and partners convened the conference Making the Planetary Boundaries Concept Work in Berlin, where policymakers, private sector and civil society jointly with scientists identified opportunities to operationalise the planetary boundaries framework.

Is it possible to have a good life for all within planetary boundaries? This is an important question.

New Zealand achieves eleventh place (Figure 24) in the 2019 SDG Index, an international league table of progress towards the Sustainable Development Goals.[8] According to the SDG Index, New Zealand has already achieved Goal 7 relating to affordable and clean energy and is on track to achieve four more goals by the 2030 deadline relating to education, gender, economic development and infrastructure. However, compared with 2018, progress on climate and biodiversity is declining and significant challenges remain for progress on the water goal. Moreover, New Zealand ranks 45th when "spillover" – impact beyond its territory – is factored in.

Figure 23: A systems view of international (blue) policy frameworks of most relevance to planetary boundaries. No global policies exist that directly tackle biogeochemical cycles (P and N) though some policy frameworks include nitrogen. While several international policies relate to novel entities, for example nuclear material, this in no way captures the risks related to the 100,000+ novel entities in the environment. We assess that most international policies relating to boundaries are too weak to support transformation towards a safe operating space for humanity.



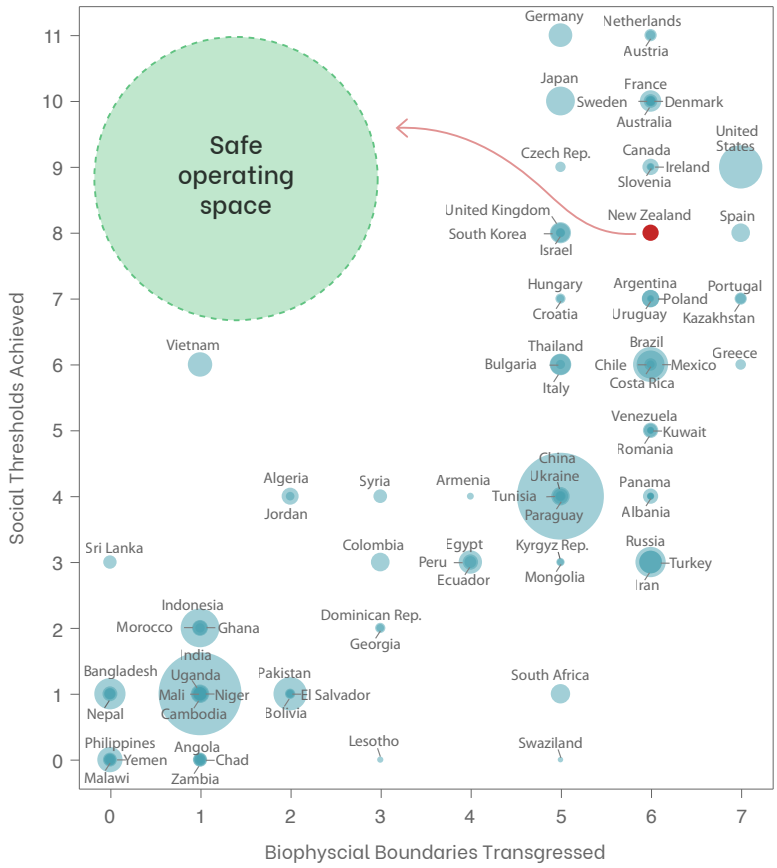
Countries at the top of the league table clearly have exceptionally high standards of well-being. However, they also significantly exceed boundaries. A 2018 analysis of 150 countries using planetary and social indicators found that "no country meets basic needs for its citizens at a globally sustainable level of resource use"[9] (Figure 25). In general, the analysis found that the more social goals a country achieves, the more biophysical boundaries the country crossed.

This is sobering news and confirms other national footprint assessments. So, should we conclude environmental health and human well-being are incompatible? No. In the past, the markets have not priced environmental externalities and producers and consumers have had little choice but adoption of practices that have taken a high toll on the environment. Now, major economies are decoupling rapidly from CO_2 emissions. We can see long-term structural shifts in economies away from fossil fuels. Technologies are now available to reduce impact in farming for example, as discussed in Chapter 3. And many improvements in human well-being can bring environmental benefits, for example a shift to healthy diets and reduction in emissions of greenhouse gases can improve biodiversity.

Figure 24: The SDG Index. New Zealand is placed 11th.

Country	Region	SDG	Rank	Score
Denmark	OECD members		1	85.2
Sweden	OECD members		2	85.0
Finland	OECD members		3	82.8
France	OECD members		4	81.5
Austria	OECD members		5	81.1
Germany	OECD members		6	81.1
Czech Republic	OECD members		7	80.7
Norway	OECD members		8	80.7
Netherlands	OECD members		9	80.4
Estonia	OECD members		10	80.2
New Zealand	OECD members		11	79.5

Figure 25: Using data relating to planetary boundaries and social indicators from 150 countries, all developed nations have significantly transgressed the assessed planetary boundaries. The "safe operating space" of high societal well-being within planetary boundaries lies in the top left quadrant. No countries currently inhabit this space. On social indicators New Zealand performs similarly to the UK, South Korea and Spain. On environmental indicators, on aggregate, New Zealand is closer to Canada, Australia or Ireland.[9]



Source: Adapted after O'Neill et al (2018) Nature Sustainability.

4.2 Towards a systems approach for New Zealand policy

Living within planetary boundaries will require a sustainability transition with a systemic shift towards more circular economies to reduce material and resource use and harmful emissions and towards more regenerative economies that build resilience in social-ecological systems. The shift must move beyond a focus on incremental reductions and look to transform an economy to store carbon rather than emit it, protect and restore ecosystems and their biodiversity rather than degrade and reduce them and improve soil and water quality rather than degrade them. This economic model will build social and ecological resilience.

The Sustainable Development Goals (2030 Agenda) encourages each government to set "its own national targets guided by the global level of ambition but taking into account national circumstances". The planetary boundaries provide the first quantitative assessment of the required global level of ambition.

The framework can inform New Zealand national policies and targets in two ways. First, it puts national agendas within a global, systemic and long-term perspective. Second, it provides a framework for policy coherence for sustainable development across policy sectors.

The translation results should not, however, be interpreted as direct policy targets for New Zealand. Translating and applying the framework at country level requires normative decisions to be made. Each nation needs to appraise its acceptable risks, its definitions of environmental justice and fairness and accordingly of common but differentiated responsibility relating to the global safe operating space. Moreover, applying this global perspective requires further analysis of related local and

Table 11: Policy instruments to support a systems-approach for planetary boundaries at national and international levels and implementation strategies (adapted from Sterner et al.[10]). Note: most national legislation relates to territorial impact.

Planetary boundary	Immediate implementation strategies	Potential national strategies	International action
1. Climate change	Eliminate fossil fuel subsidies.	Carbon pricing through taxes and/or tradable permits	Implementation of Paris Agreement pledges
2. Ocean acidification (linked to 3–5, 7–9)	Infrastructure investment (e.g., smart grids, improved transmission and distribution)	Carbon emission regulations, technology, policies for reducing all greenhouse gases	Negotiation of additional agreements and more stringent pledges as follow-up to Paris Agreement
	Facilitate breakthrough low-carbon and energy efficiency technologies through research and development (R&D) subsidies	Carbon sequestration incentives	Climate finance for mitigation in developing countries
3. Biosphere integrity	Reduction and rationalisation of agricultural, fishing, mining, forestry and aquaculture subsidies Improved regulation of primary product industries	Market-based instruments for reducing agricultural and water pollution	Regional and international agreements and coordination necessary for management of transboundary water, land and marine resources (e.g., internationally shared marine reserves and water, major river basins, deep-sea resources or forest biomes)
4. Land-system change	Water-use pricing and regulation	Water markets and trading Taxes/regulation for hazardous waste and mining	
5. Freshwater use (linked to 1, 2, 8)		Landfill and waste charges	
		New protected areas	
		Strengthen property rights	
6. Novel entities	Speed up and strengthen the US TSCA, EU REACH and similar liability and authorisation legislation Improve information on risks	Technology policies to reduce use of harmful entities	Improved coordination and additional agreements for novel entities (for example, using the Montreal Protocol on ozone regulation as a model)
7. Stratospheric ozone depletion (linked to 1–3, 9)		Taxes and regulations to control over use	
		Improved monitoring, identification and categorising	

regional contexts. The planetary boundaries framework can stimulate discussion about national allocations and responsibilities, for example relating to sustainable production and consumption, trade and environmental degradation and restoration beyond national borders.

A useful way to identify gaps and weaknesses in policies is a systems mapping of national and international policies of relevance to planetary boundaries (Figure 25). Moving from this starting point to coherent policies will require further analysis but Sterner and colleagues[10] have proposed policy instruments for a systemic approach for national and international policymaking (Table 11).

Policy coherence is required horizontally (between sectors) and vertically (between levels and scales) to support global efforts to stay within planetary boundaries. Horizontal policy coherence refers to adopting a systems approach to ensure policies that address one boundary do not make it more difficult to address other boundaries. Practically, this means policy coherence across ministries – finance, environment, industry and trade. Vertical coherence from local to national and up to the global scale will be required for countries to align their policies with the guardrails set by the planetary boundaries.

There are multiple entry points for mainstreaming the information and guidance provided by the planetary boundaries framework. Examples include New Zealand's Resource Management Act, the National Policy Statement for Freshwater Management, National Policy Statement for Indigenous Biodiversity, the Living Standards Framework and other national policies on environment, energy, agriculture, trade and (green/circular/bio) economy. A policy analysis informed by the insights from this report and jointly undertaken by policymakers and scientists can improve vertical policy coherence between the national and global level as well as horizontal policy coherence between sectors.

Opportunities for simultaneously achieving environmental, economic and social sustainability and for generating co-benefits are plentiful. For instance, globally reducing agriculture-related greenhouse gas emissions and anthropogenic aerosols will reduce air pollution avoiding millions of premature deaths globally as well as improving crop yields.[11, 12] Similarly, policies to shift towards healthier diets and improve people's well-being can also cut greenhouse gas emissions and protect biodiversity.[13] Regeneration of landscapes and applying agro-ecological principles can turn carbon sources into carbon sinks, can reduce environmental pressures and at the same time improve and ensure the long-term productivity of natural resources.

Europe is embarking on such a sustainability transition by way of its Green New Deal,[14] which treats "climate and environmental-related challenges as … this generation's defining task" and aims to "protect the health and well-being of citizens from environment-related risks". The European Green Deal roadmap includes, for example, a European climate law enshrining the 2050 climate neutrality objective, land-use regulation, a greening of the common agricultural policy, a farm-to-fork strategy, a forest strategy, an industrial strategy, a smart sector integration strategy and a zero pollution action plan.

New Zealand has multiple entry points for mainstreaming planetary boundaries into its legislation:

New Zealand's first "Wellbeing Budget" (May 2019)[15] is framed around managing the country's various resources: human capital, natural capital, social capital and financial and physical capital. For the first budget, the government, through stakeholder consultation, identified five priority areas. One area specifically addressed planetary stewardship: "Creating opportunities for productive businesses, regions, iwi and others to transition to a sustainable and low-emissions economy."

New Zealand's Wellbeing data[16] and Living Standards Framework Dashboard track changes in natural capital (e.g., GHG emissions, carbon storage, biodiversity loss, stock of freshwater resources), in human and social capital (e.g., life expectancy, education, discrimination) and physical and financial capital (e.g., productivity, investments, assets). Tracking changes and hence determining direction of change is an important complement to the assessment of the current position relative to New Zealand's fair share of the safe operating space.

Ultimately, a deeper assessment is required to analyse national policy coherence for a safe operating space for New Zealand and how coherence might be achieved.

4.3 Next steps

Several countries have commissioned similar analyses based on the planetary boundaries framework. These analyses allow countries to use a systems view to assess their global environmental responsibilities. The most recent assessment has been published by the European Environment Agency in April 2020. These assessments highlight where there are structural gaps between global ambitions of multilateral environmental agreements and national policies (Figure 3). These assessments also highlight knowledge and data gaps. The following research and translation priorities need to be addressed:

- National downscaling and translation initiatives have been led by environment ministries and academic institutions. We have observed less engagement with other ministries and relevant stakeholders. A systems view of the challenges and opportunities requires new engagement processes across sectors and ministries.
- Further development of principles, methods and parameterisations for allocating the global safe operating space to individual countries or regions, including normative decisions about acceptable risks and fair shares.
- Harmonisation of national and international data, for the analyses of national fair shares and their transgression, in particular consumption-based footprints.
- Interpretation and contextualisation of global issues at the local scale (that is sub-national level) and vice versa requires top-down/bottom-up integration of targets.
- Rapidly changing environmental conditions, pressures and knowledge require dynamic national assessments that account for these changes.
- More work is needed to link positive economic and well-being outcomes from reducing environmental impacts related to planetary boundaries.W
- National target-setting and development of underlying relevant knowledge is a co-development process, involving scientists and policymakers, which requires new ways of visualising and communicating scientific information and knowledge.
- This analysis focused on five of nine boundaries. More work needs to be done to downscale other boundaries. A key priority for the international research community is to provide first assessments of two boundaries currently unassessed: novel entities and aerosols.

References

1. N. Kanie, D. Griggs, O. Young et al., Rules to goals: emergence of new governance strategies for sustainable development. *Sustain Sci*. 14, 1745–1749 (2019).
2. Resilient People, Resilient Planet: A Future Worth Choosing. Sustainable Development Knowledge Platform. Available at https://sustainabledevelopment.un.org/index.php?page=view&nr=374&type=400&menu=35.
3. OECD, Towards Green Growth. OECD Publishing (2011). DOI: https://dx.doi.org/10.1787/9789264111318-en
4. UNEP, Global Environmental Outlook 5 (2012).
5. H. Hoff, T. Häyhä, S. Cornell, P. Lucas, Bringing EU policy into line with the Planetary Boundaries. Stockholm Environment Institute (2017).
6. EEA, FOEN. Is Europe living within the limits of our planet? An assessment of Europe's environmental footprints in relation to planetary boundaries. Joint EEA/FOEN Report, European Environment Agency (2020).
7. EEAC, Safe Operating Space: Current State of Debate and Considerations for National Policies (2014). Available at http://eeac.eu/wp-content/uploads/2016/04/Workshop-Summary-Report-2014.pdf.
8. Sustainable Development Report, available at https://www.sustainabledevelopment.report.
9. D. W. O'Neill, A. L. Fanning, W. F. Lamb, J. K. Steinberger, A good life for all within planetary boundaries. *Nature Sustainability*. 1, 88–95 (2018).
10. T. Sterner et al., Policy Design for the Anthropocene. *Nature Sustainability*. 2(1), 14–21 (2019). DOI: 10.1038/s41893-018-0194-x.
11. D. Shindell, G. Faluvegi, M. Walsh et al., Climate, health, agricultural and economic impacts of tighter vehicle-emission standards. *Nature Climate Change*. 1, 59–66 (2011).
12. D. Shindell, J. C. I. Kuylenstierna, E. Vignati et al., Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science*. 335, 183–189 (2012).
13. W. Willett, J. Rockström, B. Loken et al., Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*. 393, 447–492 (2019).
14. The European Green New Deal, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions (2019). Available at https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF.
15. The Wellbeing Budget 2019 (2019). Available at https://treasury.govt.nz/publications/wellbeing-budget/wellbeing-budget-2019.
16. Stats NZ, Wellbeing data, available at https://www.stats.govt.nz/topics/well-being.

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Figure 13: Land boundary based on cropland usage. For comparison, global average, OECD and other nations are shown (production only).

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Figure 21: The radial plot show global (top) and national (bottom) status of five planetary boundaries on a normalised scale. New Zealand exceeds its "fair share" of the global safe operating space for most production-based (territorial) and consumption-based boundaries. The safe zone is depicted in the centre, where the edge of the green circle is the normalised boundary (= 1). After boundary transgression is a zone of increasing but uncertain risks (= 1 - 2). Beyond this is a zone of high risk, depicted by the red line (= 2), which equates to boundary transgression by a factor of 2. From the red line outward, factors of transgression continue approximately according to the white lines. The scale is capped at a factor of 15. Note that phosphorus on the production side is at 55 times transgression and therefore goes off the chart.

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Figure 23: A systems view of international (blue) and New Zealand (green) policy frameworks of most relevance to planetary boundaries. No global policies exist that directly tackle biogeochemical cycles (P and N) though some policy frameworks include nitrogen. While several international policies relate to novel entities, for example nuclear material, this in no way captures the risks related to the 100,000+ novel entities in the environment. We assess that most international policies relating to boundaries are too weak to support transformation towards a safe operating space for humanity.

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Table 11: Policy instruments to support a systems-approach for planetary boundaries.

Appendix 1

Data Sources

In this analysis we do not make use of specific data drawn from New Zealand, although some indicators are available from Stats New Zealand, for example on phosphorus and nitrogen sales and water abstraction. We instead rely on globally harmonised data in order to remain consistent in terms of system boundaries for the production- and consumption-based analysis. It should be noted, however,that Stats New Zealand is the underlying reporting source for trade tables in Eora, as well as for energy, land-use and fertiliser data aggregated into the other sources for environmental indicators.

Appendix table 1 lists the underlying sources used for estimating environmental pressures for New Zealand, as well as other reference countries. Note that we list the base variables and their sources, prior to transformations necessary to perform the analysis (e.g., into per capita, or per land area variables). Where consumption-based analysis is performed (i.e., in all cases apart from forest cover and the Biodiversity Integrity Index), the same underlying sources and variable definitions are used as in the production-based analysis.

Appendix table 1: Data sources and variables for production- and consumption-based allocation of environmental pressures.

Variables	Units	Latest available year	Source
Climate			
Carbon emissions	tCO_2	2015	EDGAR emissions database (Crippa et al. 2019)[1]*
Land-use change			
Cropland area	ha	2015	Food and Agricultural Organisation of the United Nations (FAO 2019)[2]*
Forest cover area	ha	2015	Food and Agricultural Organisation of the United Nations (FAO 2019)[2]*
Freshwater use			
Blue-water use	m^3	2013	Lenzen et al. 2013[3]*
Biogeochemical flows			
Nitrogen applications	kg	2015	NASA Socioeconomic Data and Applications Center (Potter et al. 2011)[4]; Food and Agricultural Organisation of the United Nations (FAO 2019)[2]*
Phosphorus applications	kg	2015	NASA Socioeconomic Data and Applications Center (Potter et al. 2011)[4]; Food and Agricultural Organisation of the United Nations (FAO 2019)[3]*
Biosphere integrity			
Biodiversity integrity index (BII)	1-100	2005	Sanchez-Ortiz et al. (pre-print)[5]
Mean Species Abundance	1-100	2010	GLOBIO3 (Alkemade et al. 2009)[6]
Additional variables for the translation analysis			
Population	persons	2018	United Nations Department of Economic and Social Affairs (UN DESA 2019)[7]
Gross Domestic Product	US$	2017	World Bank 2019[8]
Total land area	ha	2015	Food and Agricultural Organisation of the United Nations (FAO 2019)[2]*

In rows marked * data was taken from the Eora database,[9] which itself draws from the listed underlying data sources.

For nitrogen and phosphorus nutrient applications, the indicators we use in Eora draw from spatially explicit fertilizer application data estimated by Potter et al.,[4] aggregated to a national level. Application refers to the quantity of nutrients applied to cropland, and does not include manure from livestock, industrial uses, and non-cropland applications. This data has further dependencies on FAO reporting, which draws from questionnaires and national sources such as Stats NZ. It should be noted that there is a strong concurrence between levels of production-based phosphorus application reported in Eora and Stats NZ (1.6E8 and 1.7E8 kg in 2015, respectively). However these differ substantially from FAO sources (5.4E8 kg). By contrast, there is a concurrence between FAO and Stats NZ sources for nitrogen application (4.3E8 and 4.3E8 kg in 2015), but not to Eora (1.7 E8 kg). The differences between these datasets may be attributable to varying underlying sources, aggregation methods, or system boundaries. FAO data, for example, includes fertilisers applied to all land types, but is not specific on whether industry or household use is excluded at a country level. Stats NZ refers to application on land, but is not specific regarding the

particular land types. This underlines the need to better understand national uses of fertilisers and their relation to internationally reported data (alongside other environmental indicators), as well as develop dedicated input-output models to situate New Zealand's trade-related impacts using local data where possible (a non-trivial task). In summary, the Eora data we use lies at the lower bound of both nitrogen and phosphorus nutrient applications, and hence is likely conservative. More pragmatically, however, since this data is situated within an MRIO setting, it allows us to calculate and compare both production and consumption based application impacts.

With these caveats in mind, and in addition to applications, we also report from a dedicated Eora study on nitrogen emissions footprints.[10] This study compiles FAO and International Fertiliser Association (IFASTAT) data on land use (crop/livestock) types and nitrogen applications. It estimates per activity and country nitrogen emissions using the IPCC nitrogen flow model and allocates these to producers and consumers through the Eora MRIO model. As we report in the main text, this analysis again confirms high per capita nitrogen footprints within New Zealand (48kg N/capita/year). These are within the range of other highly developed countries, and beyond the planetary boundary for global nitrogen emissions[11] (approx. 3.9 kg N/capita/year). More notably, it places New Zealand as the 6th highest international exporter of nitrogen emissions, confirming the direction of production/consumption based biogeochemical impacts in New Zealand (higher production, lower consumption, large exports), as well as the extreme magnitude of domestic nitrogen impacts for a small country.

Appendix table 2: Total and relative values for consumption- and production-based environmental indicators in New Zealand

Indicator	Total value	Unit	Per capita or per land area value	Unit	Boundary value
CO_2 emissions consumption	42,945,096	tCO_2	9.31	tCO_2/capita	1.85
CO_2 emissions production	33,660,238	tCO_2	7.29	tCO_2/capita	1.85
Nitrogen use consumption	74,655,486	kg	16.18	kg/capita	8.12
Nitrogen use production	166,201,230	kg	36.02	kg/capita	8.12
Phosphorus use consumption	59,705,084	kg	12.94	kg/capita	0.81
Phosphorus use production	169,642,830	kg	36.76	kg/capita	0.81
Water use consumption	3,889,011,329	m^3	843	m^3/capita	524
Water use production	3,629,291,245	m^3	787	m^3/capita	524
Cropland consumption	N/A		0.05	% total land	0.15
Cropland production	N/A		0.02	% total land	0.15
Forest cover production	N/A		0.55	% missing potential forest cover	0.50
Biodiversity loss production	N/A		42.00	BII (inverted)	10.00

Population data used for the planetary boundary translation and MRIO analysis are from the United Nations Department of Economic and Social Affairs[7] available for the historical period 1959–2017. Key to this analysis was globally harmonised national population data from the most recent year on record, given the most recent year available for the given boundary metric.

Population projections to the year 2050 were used in the EAT-Lancet report environmental target analysis and therefore underlie analysis in the food-sector case study. These projections come from the Shared Socioeconomic Pathways "middle of the road" scenario (SSP2),[12] which is compared to the UN DESA data in Appendix table 3, and described in full here:

Appendix table 3: SSP2 population estimates with UN historical data in parenthesis where applicable.

Year	New Zealand	World
2005	4,132,717 (4,135,355)	6,498,914,465 (6,542,159,383)
2010	4,368,136 (4,370,062)	6,879,479,787 (6,958,169,159)
2015	4611420 (4614532)	7,258,483,157 (7,383,008,820)
2020	4,851,529	7,626,353,485
2030	5,279,569	8,279,769,922
2040	5,632,778	8,806,207,756
2050	5,939,593	9,187,191,632

References

1. M. Crippa et al., Fossil CO_2 and GHG emissions of all world countries - 2019 Report, EUR 29849 EN, Publications Office of the European Union, ISBN 978-92-76-11100-9, doi:10.2760/687800, JRC117610 (2019).
2. FAO, Food and Agriculture Organisation of the United Nations: FAOSTAT Database Online (2019). Available at http://faostat.fao.org/.
3. M. Lenzen, D. Moran, A. Bhaduri et al., International trade of scarce water. *Ecological Economics*. 94, 78-85 (2013).
4. P. Potter, N. Ramankutty, E.M. Bennett, and S.D. Donner. Global Fertilizer and Manure, Version 1: Phosphorus Fertilizer Application. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). (2011). Available at: http://dx.doi.org/10.7927/H4FQ9TJR.
5. K. Sanchez-Ortiz, R. E. Gonzalez, A. De Palma et al., Land-use and related pressures have reduced biotic integrity more on islands than on mainlands. *bioRxiv* (pre-print). Available at https://doi.org/10.1101/576546.
6. R. Alkemade, M. van Oorschot, L. Miles et al., GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss. *Ecosystems*. 12(3) 374–390 (2009).
7. UN DESA 2018 World Urbanization Prospects: The 2018 Revision (New York: United Nations, Department of Economic and Social Affairs, Population Division).
8. World Bank, World Bank Development Indicators Online (2019). Available at http://data.worldbank.org/.
9. M. Lenzen, K. Kanemoto, D. Moran, A. Geschke, Mapping the structure of the world economy *Environ. Sci. Technol.* 46, 8374–81 (2012).
10. A. Oita, A. Malik, K. Kanemoto, et al., Substantial nitrogen pollution embedded in international trade. *Nat. Geosci.* 9, 111–115 (2016).
11. EEA, FOEN, Is Europe living within the limits of our planet? An assessment of Europe's environmental footprints in relation to planetary boundaries. Joint EEA/FOEN Report, European Environment Agency (2020).
12. K. Riahi et al., The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview (2016). Available at https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Appendix 2

Methods

Planetary boundary translations

For the five boundaries assessed in this report, the equations are shown for calculation global shares and national translations according to methods for 1) cumulative budgets, 2) annual budgets, and 3) percentages and indices.

1. Cumulative Budgets: Climate Change

Conversions
1 gigatonne (Gt) = 1,000,000,000 tonnes (t)

Global per capita shares: Per capita emissions based on constant rates allocation of the remaining carbon budget in Table 3. Equal rates allocation, 2050 or 2100 time horizon:

$$PB_g = \frac{B_t / T_f - T_c}{P_g}$$

Where PB_g is the global boundary (CO_2 cap yr^{-1}), P_g is the global population in the reference year, T_f is the last year of the time horizon (e.g. future), T_c is the reference year (e.g. current year), and B_t is the total remaining CO_2 budget.

National total shares:

$$PB_n = PB_g \times P_n$$

Where PB_n is the national share of the remaining global carbon budget, PB_g is the global boundary (CO_2 cap yr^{-1}), and P_n is the current national population.

1. Annual Budgets: Biogeochemical flows, Freshwater

Conversions
1 teragram (Tg) = 1 megatonne (Mt) = 1,000,000,000 kilogram (kg)

1 cubic kilometre (km^3) = 1,000,000,000 cubic metre (m^3)

Global equal per capita allocation:

$$PB_g = \frac{B_t}{P_g}$$

Where PB_g is the global equal-per-capita boundary (i.e. Tg N yr^{-1}, Tg P yr^{-1}, or km^3 water yr^{-1}), B_t is the total annual budget, and P_g is the global population in the reference year.

National equal-per-capita allocation:

$$PB_n = \frac{PB_g}{P_g}$$

Where PB_n is the national equal-per-capita boundary (i.e. Tg N yr^{-1}, Tg P yr^{-1}, or m^3 water yr^{-1}), is the global equal-per-capita boundary (i.e. Tg N yr^{-1}, Tg P yr^{-1}, or km^3 water yr^{-1}), and P_n is the national population in the reference year.

2. Percentages/Indices: Land-system change, Biosphere Integrity

Both cropland and forest-cover boundaries are expressed as percentages of land, therefore the metrics apply the same at global and national scales.

Both BII and MSA are indices, therefore, the metrics apply in the same way to global and national scales.

MRIO Methods

Input-output analysis in a multiregional setting (otherwise known as "multiregional input-output" or MRIO analysis) is used to estimate the consumption-based environmental footprints of New Zealand. MRIO has reached a high level of standardisation in the literature and remains the principal approach used to calculate national environmental footprints.[1–3]

The core of MRIO analysis is a Leontief input-output (IO) equation (hereafter denoted as L) showing the relationships between products and industries:

$x = (I - A)^{-1}y$

where output (x) is described as a function of final demand in New Zealand (y), moderated by the identify matrix (I) and technical coefficient matrix (A). The Leontief inverse, $(I-A)^{-1}$, is a matrix where each column describes the total inputs required to produce one output unit of the sector linked to that column.[3] This basic framework can be extended to estimate the environmental footprints produced by changes in final demand:

$q = fLy$

where total environmental footprint (q) is a function of a coefficient vector representing environmental footprint per unit of output (f), the Leontief equation (L) and final demand (y). This equation reallocates the emissions or environmental pressures associated in every sector required to produce a given product to final demand.[3]

We use the Eora MRIO database to depict New Zealand's economy and 186 other countries in the world, with 127 sectors including all trade relationships in intermediate and final products. Eora is widely used in the literature on environmental footprinting and global trade.[4]

References

1. J. C. Minx, T. Wiedmann, R. Wood et al., Input–Output Analysis and Carbon Footprinting: an Overview of Applications. 21 (2009). Available at http://www.tandfonline.com/doi/abs/10.1080/09535310903541298.
2. G. P. Peters, E. G. Hertwich, CO_2 Embodied in International Trade with Implications for Global Climate Policy. *Environ. Sci. Technol.* 42, 1401–7 (2008).
3. A. Owen, K. Steen-Olsen, J. Barrett, T. Wiedmann, M. Lenzen, A Structural Decomposition Approach to Comparing Mrio Databases. *Econ. Syst. Res.* 26 262–83 (2014). Available at https://doi.org/10.1080/09535314.2014.935299.
4. M. Lenzen, K. Kanemoto, D. Moran, A. Geschke, Mapping the structure of the world economy. *Environ. Sci. Technol.* 46, 8374–81 (2012).