PBL Netherlands Environmental Assessment Agency

USING PLANETARY BOUNDARIES TO SUPPORT NATIONAL IMPLEMENTATION OF ENVIRONMENT-RELATED SUSTAINABLE DEVELOPMENT GOALS

Background Report

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Using planetary boundaries to support national implementation of environment-related Sustainable Development Goals

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A summary of this report has been published separately as a policy brief: *Lucas P. and Wilting H. (2018), Towards a Safe Operating Space for the Netherlands: Using planetary boundaries to support national implementation of environment-related SDGs.*

PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the field of environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all our studies. We conduct solicited and unsolicited research that is both independent and scientifically sound.

Contents

1 Introduction

It has become increasingly clear that collective human activity has significant impact on the natural environment and, if continued unchecked, could have serious repercussions for human well-being and sustainable development (MA, 2005; UNEP, 2012; IPCC, 2014). Many anthropogenic drivers—including urbanisation, population, GDP and the demand for food, energy and water—have increased significantly, since 1950 (Steffen et al., 2015a). Together, they have brought the Earth into the Anthropocene, the proposed new epoch defined by humanity’s impact on the planet, significantly modifying its components and disturbing natural cycles (Crutzen and Stoermer, 2000). Degrading or even losing vital ecosystem services can negatively impact human security and health (MA, 2005). Reversing or weakening these trends is a real challenge.

This challenge is being addressed, globally, by a range of multilateral environmental agreements. In 1972, as part of the United Nations Conference on the Human Environment, countries worldwide agreed that natural resources should be safeguarded and pollution should not exceed the environment’s capacity to clean itself (UN, 1972). Since 1972, a range of UN conferences, summits and multilateral agreements have set targets for sustainable human development, which in 2015/2016 culminated in the formulation of five global agreements[1] that build on and incorporate earlier agreements, most notably the 2030 Agenda for Sustainable Development (UN, 2015). The 2030 Agenda sets out a long-term global vision for sustainable development—the 17 Sustainable Development Goals (SDGs) and 169 underlying targets—to achieve a prosperous, socially inclusive and environmentally sustainable future for humanity and the planet. From an environmental perspective, it aims to steer human development towards a safe and just operating space for society to thrive in. Safe, as in avoiding the negative impacts of global environmental change for people worldwide, and just, as in ensuring that all people can enjoy access to the resources that underlie human well-being, now and in the future.

The 2030 Agenda stresses the importance of proportionate contributions by all countries and actors. It calls on governments to set their ‘own national targets guided by the global level of ambition but taking into account national circumstances’ (UN, 2015; Paragraph no. 55). The Netherlands has committed to the full implementation of the 2030 Agenda (BZ, 2016). A baseline measurement of where the country stands in terms of achieving the SDGs, shows that although the Netherlands is making progress, there are important areas of concern, including high greenhouse gas emission levels and relatively high environmental pressure being exerted on other countries, particularly in the developing world (CBS, 2016; Kingdom of the Netherlands, 2017). Defining a national ambition level for environment-related SDG targets can build on a broad range of current policy targets to which the Netherlands has already committed. However, these targets mostly address environmental pressures and impacts within national borders. Furthermore, these targets need to be updated and further aligned with the corresponding SDG targets, in terms of both ambition level and target horizon (Lucas et al., 2016). The 2030 Agenda leaves ample room for interpretation. It is unclear about the level of global environmental change that needs to be avoided. Many SDG targets that address global environmental challenges (e.g. climate change, nutrient pollution, biodiversity loss) are defined at the global level and phrased in non-quantitative terms. Furthermore, the 2030 Agenda provides little guidance on how to translate global SDG ambitions into national targets and policies.

Setting global quantitative targets and translating them into national targets and policies is a primarily political process. The 2030 Agenda includes a range of global environmental challenges to which the global community has committed. However, with the exception of climate change (in the Paris Agreement), there are no globally agreed quantitative policy targets related to these challenges. Defining global quantitative targets in areas where they currently do not exist, involves normative decisions related to risk acceptance, solidarity and precaution. Science can help by providing insights into societal risks of various levels of global environmental change. The next step, scaling global quantitative targets to national levels, requires normative choices with respect to equity, environmental justice, burden sharing, and allocation of scarce resources. Science can help by systematically evaluating country-level implications of various distributive choices.

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[1] These five agreements include 1) the Sendai Framework for Disaster Risk Reduction; 2) the Addis Ababa Action Agenda; 3) the 2030 Agenda for Sustainable Development; 4) the Paris Agreement; and 5) the New Urban Agenda. See also (PBL, 2017: pp. 10-11).

The planetary boundaries framework, and the related literature that emerged since its first publication in 2009, can help setting global quantitative targets (Häyhä et al., 2016; Hoff and Alva, 2017; Hoff et al., 2017). The framework identifies precautionary limits to environmental modification, degradation and resource use. Together, the planetary boundaries define levels of global environmental change in which the risks are considered manageable, i.e. a global 'safe operating space' for human development (Rockström et al., 2009; Steffen et al., 2015b). Scaling global quantitative targets to national levels essentially divides up global resource budgets or reduction objectives. In the climate change negotiations and the literature, many proposals for a fair and equitable sharing of emission reduction obligations have been submitted and discussed, based on a range of equity principles, i.e. general concepts of distributive fairness (Fleurbaey et al., 2014). There is no global consensus on what can be considered a fair and equitable distribution. What would produce a favourable result differs per country. Various approaches, based on different underlying equity principles, could be used to assess if a country's pledge corresponds with what could be considered 'fair'. Furthermore, countries themselves can use scientific insights into distributive fairness when setting their own national targets, i.e. national fair shares. Finally, footprint indicators, taking into account environmental pressures and impacts along the whole value chain related to national consumption, can be used as benchmarks against national targets. Footprint indicators are particularly relevant for evaluating country performance on global issues (Dao et al., 2018). Environmental footprints have been calculated for a variety of environmental pressures, impacts and resource uses (Wiedmann and Lenzen, 2018) and are discussed within the context of the SDGs (Gómez-Paredes and Malik, 2018; Sachs et al., 2018).

In this study, we discuss normative choices that are needed for translating global environment-related SDG ambitions into national policy targets, and the possible role of science. Furthermore, we discuss what various choices would mean for the Netherlands. More specifically, we analyse what would be a safe operating space for the Netherlands, and whether the country currently is functioning within this calculated safe operating space. The analysis is based on scientific insights into planetary boundaries and fair and equitable distribution from the climate change literature and national footprints indicators. It provides insights into the order of magnitude of Dutch policy targets that are in line with the global SDG ambitions for a range of global environmental challenges, including climate change, land-use change, nutrient pollution (nitrogen and phosphorus) and biodiversity loss.

This study builds on earlier research conducted within the planetary boundaries research network (PB.net).[2] The global limits, as defined by the planetary boundaries framework, are used as a set of science-based targets to quantify environment-related SDG targets. We use the planetary boundaries framework as it is now. Nevertheless, we are critical in our interpretation, and focused on a subset of boundary processes for which we believe a global perspective has added value and used alternative metrics where relevant. The scaling of the planetary boundaries to a national safe operating space uses the framework developed by Häyhä et al. (2016) and allocation approaches from the climate change literature (Van den Berg et al., submitted). Footprint indicators, taking into account environmental impacts along the whole value chain, are used to measure current environmental pressures related to Dutch national consumption. The footprint indicators are based on PBL studies and were updated where necessary. Furthermore, the analysis builds on lessons from earlier operationalisation studies, including on Sweden (Nykvist et al., 2013), Switzerland (Dao et al., 2015; Dao et al., 2018) and the EU (Hoff et al., 2014; Hoff et al., 2017; Häyhä et al., 2018), and links to the work of PBL's IMAGE team on global environmental change scenarios (Stehfest et al., 2014), using their latest long-term projections (Van Vuuren et al., 2017c).

[2] The Planetary Boundaries Research network (http://www.pb-net.org) is a collaboration of the Stockholm Resilience Centre (SRC), Stockholm Environment Institute (SEI), the Potsdam Institute for Climate Impact Research (PIK) and PBL Netherlands Environmental Assessment Agency.

2 Methodology

Translating environment-related sustainable development goals (SDGs) into national policy targets requires defining global quantitative targets where they currently do not exist, and determining individual country's 'fair' share of the related safe operating space or contribution towards mitigating global environmental pressures and impacts. Here, we present the planetary boundaries framework as a set of global science-based targets, discuss their link with the SDGs, and describe the steps required to translate global limits, as defined by selected planetary boundaries, into national policy targets, taking into account lessons from previous translation studies.

2.1 The planetary boundaries framework

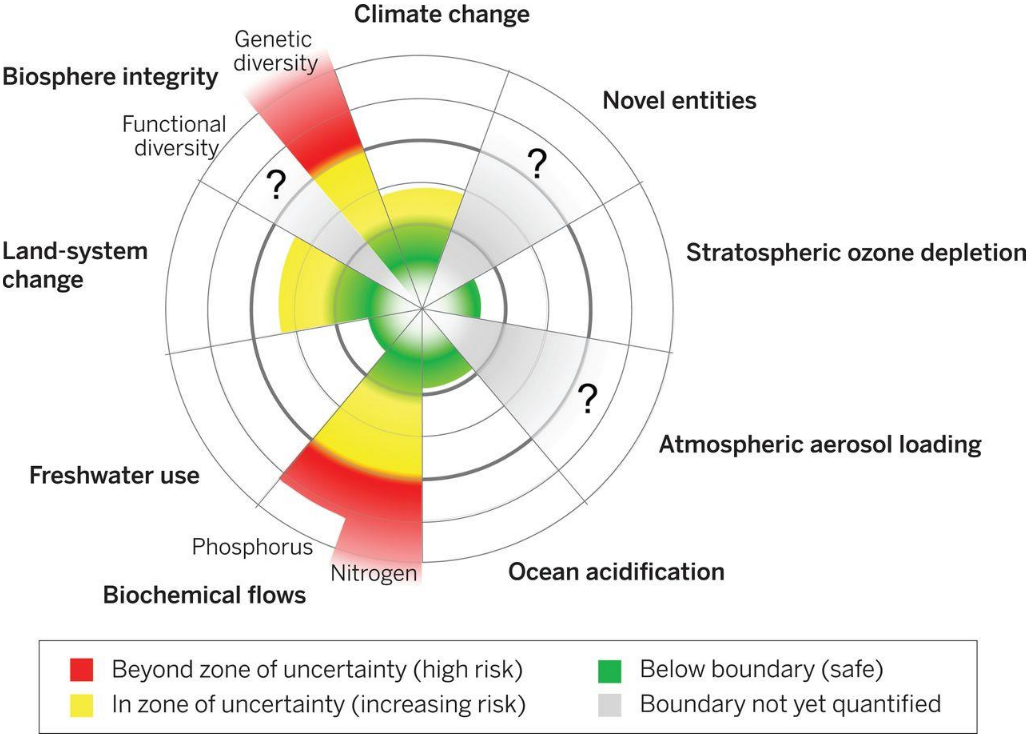
The core of the global environmental challenge is that there are limits to the availability of environmental resources (e.g. land and water) and to the Earth's capacity to absorb increased pollution (e.g. CO_2 emissions), while at the same time people are dependent on the goods and services that the Earth's system provides (e.g. food, water and energy security). Twentieth century human development has brought the Earth into the Anthropocene, the proposed new geological epoch defined by humanity's impact on the planet (Crutzen and Stoermer, 2000). A sharply increasing population, especially in urban areas, alongside strong economic growth, has resulted in a rising demand for natural resources, including food, water and energy. Although economic growth has improved human well-being, growth in the demand for resources has put increasing pressure on the global environment (Steffen et al., 2015a; PBL, 2017: pp. 6–7).

In response to these developments, Rockström et al. (2009)—later updated by Steffen et al. (2015b)—developed the planetary boundaries framework. The planetary boundaries framework takes environmental stability as an important enabler of human development, using the comparatively stable biophysical conditions of the Holocene as the baseline level, which has been relatively stable and hence beneficial for human development. It defines a set of quantitative physical limits for nine critical Earth system processes for the extent of human perturbation to these processes, building upon the precautionary principle. Crossing any of the boundaries on a global scale increases the risk of large-scale, possibly abrupt or irreversible environmental change, undermining the resilience of the Earth system as a whole and impacting human well-being. The concept builds on the literature on global and sub-global systemic thresholds and regime shifts. Furthermore, it combines Earth system science with resilience thinking and builds on earlier concepts, such as limits to growth (Meadows et al., 1972), critical loads (UNECE, 1979) and carrying capacity (Daily and Ehrlich, 1992).

The nine planetary boundaries cover physical, chemical and biological processes of the Earth system, i.e. climate change, biosphere integrity, biogeochemical flows, land-system change, ocean acidification, freshwater use, stratospheric ozone depletion, novel entities and atmospheric aerosol loading. For most boundary process, control variables are defined to assess the extent to which individual boundaries are transgressed. Accordingly, four boundaries are identified as being transgressed already: climate change, biosphere integrity, land-system change and biogeochemical flows (Figure 1). Climate change and land-system change are presented in the zone of uncertainty, which encapsulates both gaps and weaknesses in the scientific knowledge base and intrinsic uncertainties in the functioning of the Earth system. At the lower end of this zone, current scientific knowledge suggests that there is very low probability of crossing a critical threshold or substantially eroding the resilience of the Earth system. Beyond the uncertainty zone, current knowledge suggests a much higher risk of large-scale, possibly abrupt or irreversible environmental change. Applying the precautionary principle, the planetary boundary is set at the lower end of the zone of uncertainty.

Figure 1

Current status of the control variables for seven of the planetary boundaries



Source: Steffen et al. (2015b)

The global research community has taken up the planetary boundaries concept as a scientific agenda by improving assessments of the individual boundary issues (Carpenter and Bennett, 2011; Gerten et al., 2013; Mace et al., 2014), proposing alternative boundary processes (Running, 2012), discussing the nature of thresholds (Barnosky et al., 2012), developing new approaches to address their complex interactions and human impacts (De Vries et al., 2013; Van Vuuren et al., 2016) and providing insights into multiple framings that could support the implementation of the SDGs (Hajer et al., 2015; Häyhä et al., 2016). This process of updating and fine-tuning is still ongoing.

Furthermore, the planetary boundaries framework has generated significant interest beyond the scientific community, including for countries and business. For example, respecting planetary boundaries is framed as the central challenges for Germany's Integrated Environmental Programme 2030 (BMUB, 2016) and the framework is referred to in the Swiss Green Economy action Plan.[3] The concept was also prominent in the drafting of the SDGs (UN, 2015) and was central to the European Union's 7th Environment Action Programme (EAP) that sets out the EU-wide ambition of 'Living well, within the limits of our planet' (EU, 2013). The One Planet Thinking Initiative, led by the World Wildlife Fund (WWF), was developed to help companies to define sustainable targets in line with the Earth's capacity (e.g. Sabag Muñoz and Gladek, 2017).

It should be noted that the set of limits proposed by the planetary boundaries framework should not be confused with targets. They are not supposed to be reached, but instead act as an upper bound. For those boundaries that are already transgressed, the limits could be used as targets. Setting global targets informed by these limits involves normative decisions related to risk acceptance (what level of global environmental change could be considered manageable), solidarity (are the expected societal impacts greater in other parts of the world and should this be taken into account) and precaution (how to account for uncertainties in the expected impacts).

[3] https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/info-specialists/green-economy/dialog.html

2.2 Planetary boundaries and the SDGs

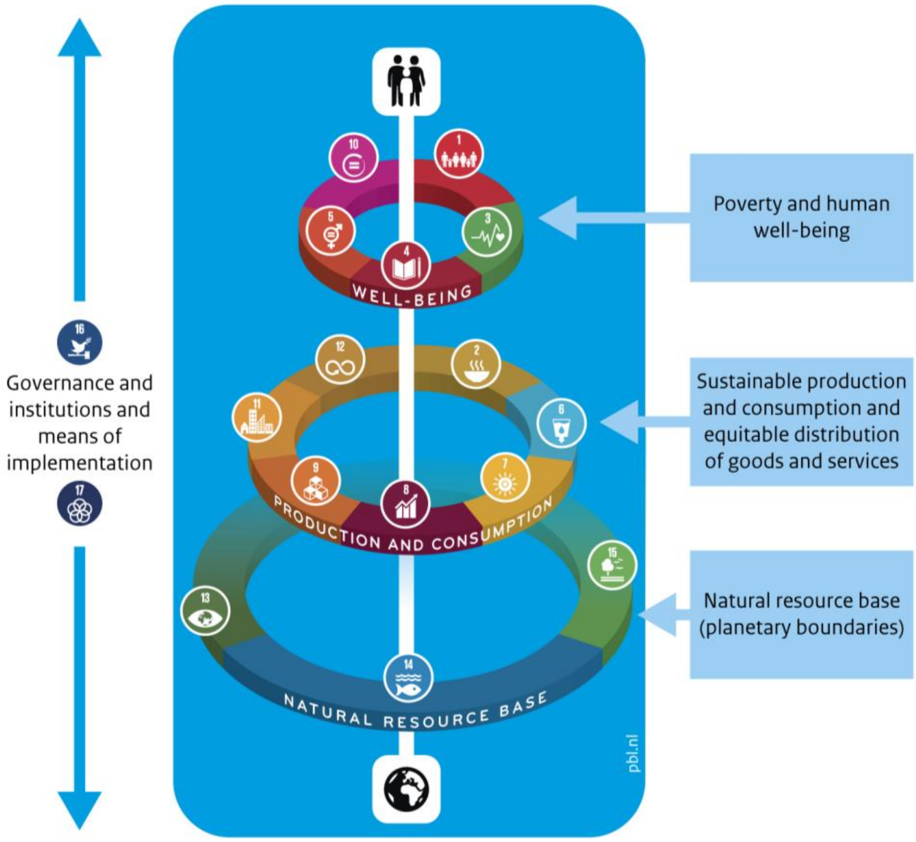
Although the planetary boundaries framework was designed to advance Earth system science, it can also be considered in the context of a much wider sustainable development agenda. Kate Raworth combined the concept of planetary boundaries with social boundaries (e.g. food security, energy access, health care, education, gender equality) and called the 'doughnut-shaped' area between the two boundaries the *safe and just operating space, in which humanity can thrive* (Raworth, 2012, 2017). Moving into this space demands far greater equity—within and between countries—in the use of natural resources, and far greater efficiency in transforming those resources to meet human needs (Raworth, 2012).

Since its publication in 2009, the planetary boundary concept attracted considerable attention in the policy sector, especially in combination with the social floor of Raworth (2012). The concept was prominent in the drafting of the 2030 Agenda for Sustainable Development and the 17 SDGs (UN, 2015). While the planetary boundaries are not mentioned explicitly in the 2030 Agenda, all nine of its system processes are addressed in some way, either as the focus of a specific SDG (freshwater use, climate change and biodiversity) or included in a target (ocean acidification, atmospheric aerosol loading, biogeochemical flows, land use change, stratospheric ozone depletion, novel entities).

Table 1
Planetary boundaries and related SDG targets (based on Häyhä et al., 2018).

Planetary boundary	Related SDG targets
Climate Change	13.2: Integrate climate change measures into national policies, strategies and planning
Ocean acidification	14.3: Minimise and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels
Stratospheric ozone depletion	12.4: By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimise their adverse impacts on human health and the environment.
Change in biosphere integrity	15.5: Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species
Land-system change	15.2: By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally 15.3: By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world
Biogeochemical flows (nitrogen and phosphorus cycles)	2.4: By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, help maintain ecosystems, strengthen capacity for adaptation to climate change, extreme weather, and other disasters and progressively improve land and soil quality 14.1: By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution.
Freshwater use	6.4: By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals.
Atmospheric aerosol loading	3.9: By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination. 11.6: By 2030 reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality, municipal and other waste management.
Introduction of novel entities	3.9: By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination. 6.3: By 2030 improve water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and increasing recycling and safe reuse globally. 12.4: By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimise their adverse impacts on human health and the environment

Figure 2
Classification and clustering of SDGs



Source: PBL

Source: Adapted from PBL (2017) and Lucas et al. (2016)

Broadly, the SDGs can be clustered in three groups (Figure 2; Lucas et al., 2016). The top cluster with people at the centre contains social goals. These goals can be considered as minimum standards for human well-being. Achieving these goals relies on goals that relate to production, consumption and distribution of goods and services (middle cluster). From an environmental perspective these goals address decoupling of human development from environmental degradation in different contexts. The Government-wide programme for a Circular Economy, the upcoming Energy Agreement, and discussions around a transition in food and agriculture provide national entry points for operationalisation for these goals. Finally, realisation of these resource and economy goals depends on conditions in the biophysical systems or natural resource base (bottom cluster), including climate, oceans, land and biodiversity (parts of SDG6 on fresh water also fit here). These goals address protection, conservation, restoration and sustainable use of critical parts of the Earth system and directly relate to the planetary boundaries. Many of these goals link to the planetary boundaries (see Table 1). The three clusters are underpinned by goals addressing governance (SDG 16) and means of implementation (SDG 17).

It should be noted that each SDG is operationalised by multiple targets, which can be classified differently. For example, SDG2 includes targets related to human well-being, such as reducing hunger and malnutrition, to sustainable resource use, such as promoting sustainable agriculture, and to the natural resource base, such as maintaining agricultural biodiversity. Hence, some planetary boundaries are also addressed by SDGs not grouped under natural resource base.

The three clusters of SDGs are bi-directionally connected in the sense that the environment provides the natural resource base on which human development and ultimately human well-being is built, while unsustainable resource use can have an adverse impact on both the environment and human well-being. The clustering links to the *safe and just operating space* of Raworth (2012), with the social foundation at the top and the planetary boundaries at the bottom. Translating the planetary boundaries into national levels can help in operationalising the SDGs at the national level.

2.3 Translating planetary boundaries into national targets

Translating global limits, as defined by the planetary boundaries, into national policy targets requires addressing the biophysical, socio-economic, and ethical dimensions of the individual planetary boundary processes (Häyhä et al., 2016). The *biophysical dimension* deals with the temporal and spatial scales at which the boundary processes take place and the particular processes, interactions and feedbacks that dominate at those scales. The *socio-economic dimension* addresses differences in natural resource use, emissions and environmental impacts between countries, including the role of international trade. The *ethical dimension* takes into account the differences between countries' and individuals' rights, abilities, and responsibilities with respect to resource use and environmental impacts.

In the next three sections, we discuss the three dimensions in the context of our study, focusing on 1) the biophysical characteristics of the planetary boundaries and the implications for selected control variables and global limits; 2) measuring countries' environmental pressures and impact on planetary boundaries; and 3) ethical considerations of scaling the planetary boundaries to the national level, i.e. a national safe operating space. These three dimensions link well to the 8-step framework of the 'One Planet Approaches', developed to translate critical planetary limits into targets for companies: 1) defining global limits; 2) information feedback and decision-making; and 3) allocation (Sabag Muñoz and Gladek, 2017).

2.3.1 Biophysical characteristics

The global boundaries, or thresholds, are defined as 'non-linear transitions in the functioning of coupled human–environmental systems', with transitions here being abrupt changes in specific Earth system processes (Rockström et al., 2009). Boundary processes differ with respect to their spatial scope and limit (Dao et al., 2015; Häyhä et al., 2016). The spatial scope relates to the level on which a specific biophysical process takes place, e.g. global or regional/local. The spatial limit relates to the level at which the threshold manifests itself, e.g. global or regional. While the existence of a global limit for planetary boundaries with a global scope is straightforward, the existence of a global limit for the environmental issues with a regional scope is much more debated. Three categories of processes can be distinguished (Dao et al., 2015):

1. For global systemic processes, human activities are introducing a direct perturbation to an Earth system component (i.e., atmosphere, ocean, biosphere). For these processes, the absolute magnitude of the pressure is what determines the overall impact, and it does not substantially matter where this pressure takes place. The processes that can be included in this category are climate change, ocean acidification and stratospheric ozone depletion. Their pressures, emissions of greenhouse gases and ozone-depleting substances, accumulate and become well mixed in the atmosphere. These processes are global by nature and a global limit exists per definition.

2. For global cumulative processes, human activities impact the Earth system at the local or regional scale. For these processes, scientific understanding is growing that local changes can cascade through the global Earth system, creating physical and biogeochemical feedbacks. Although there are no known global scale thresholds, a global limit could be identified because cumulated effects can have global scale impacts. For example, land-use change may, through a continuous decline in key ecological functions (e.g. carbon sequestration), cause functional collapse, generating feedbacks that trigger or increase the likelihood of a global threshold being exceeded in other processes (e.g. climate change). The processes in this category include biosphere integrity, biogeochemical flows (nitrogen and phosphorus) and land-system change.

3. For regional processes, human activities impact the Earth system at the local or regional scale, while there are no known global scale thresholds and rationales are currently lacking for setting a potential limit. The processes in this category include atmospheric aerosol loading, freshwater use and novel entities.

The planetary boundaries are further defined by biophysical 'control variables', indicating the physical state of a specific process (e.g. atmospheric CO_2 concentration, biodiversity intactness), but sometimes also specific human pressures on the Earth system (e.g. phosphorus flow from freshwater systems into the ocean) (Rockström et al., 2009; Steffen et al., 2015b). The scientific debate on control variables for the different planetary boundaries is ongoing. To identify appropriate indicators that can indeed be controlled and where national performance can be measured, there is a need to establish more clearly the causal chains associated with each boundary (Nykvist et al., 2013). The Driver-Pressure-State-Impact-Response (DPSIR) framework—a commonly used framework for environmental indicators (OECD, 1993; EEA, 1999)—can help to structure the causal links and interdependencies of human activities (drivers/pressures) and environmental outcomes (state/impact) and thereby the selection of metrics and targets (Nykvist et al., 2013; Dao et al., 2015). Where an indicator at state or impact level seems the closest to the essence of a planetary boundary, only indicators at driver or pressure level can directly be controlled or changed by humans and are thus relevant for determining individual country contributions towards mitigating global environmental change. The majority of the control variables proposed by Rockström et al. (2009) and Steffen et al. (2015b) are state or impact indicators.

Finally, the boundary processes and their control variables differ from a temporal perspective, defining budgets over time or annual budgets (Dao et al., 2015; Häyhä et al., 2016). For example, for climate change, a global CO_2 budget can be identified, being the maximum amount of CO_2 emissions that could still be emitted worldwide while staying below a specific temperature target (budget over time). The impact of CO_2 emissions on climate change is cumulative and therefore the current CO_2 emissions reduce the amount that could still be emitted in the future. For other processes, such as land-system change, the global budget remains constant (annual budget). The total amount of land available for cropland can be used annually, and current use, if done sustainably, will not interfere with future availability. The consideration of time is important for translating global boundaries into national policy targets, as it interacts with concepts of intragenerational and intergenerational equity and burden sharing (see Section 2.3.3 on the ethical dimension).

2.3.2 Environmental pressures and impacts

Increasing anthropogenic environmental pressures are the result of a growing population, economic development and changes in consumption patterns. Furthermore, as a result of international trade and globalisation, the effects of non-sustainable practices in one country are also felt in other countries. On the one hand, international trade is a means to make overall production more efficient and allows countries to cope with local environmental constraints. For example, water intensive commodities can be imported from water abundant areas to water scarce areas. On the other hand, international trade can lead to displacement of environmental impacts beyond national borders. For example, agricultural products imported to feed animals, can be associated with land-use change, nitrogen and phosphorus disposition and biodiversity impacts in other countries. As a result, the production (and its potential environmental impact) and consumption of goods and services increasingly happens in different locations and reduced environmental pressure in one country may come at the cost of increasing impact elsewhere, mostly developing countries (Wiedmann and Lenzen, 2018). Furthermore, relocation could also lead to an overall increase in environmental impacts, as production in developing countries tends to be more ecologically intensive (Wiedmann and Lenzen, 2018).

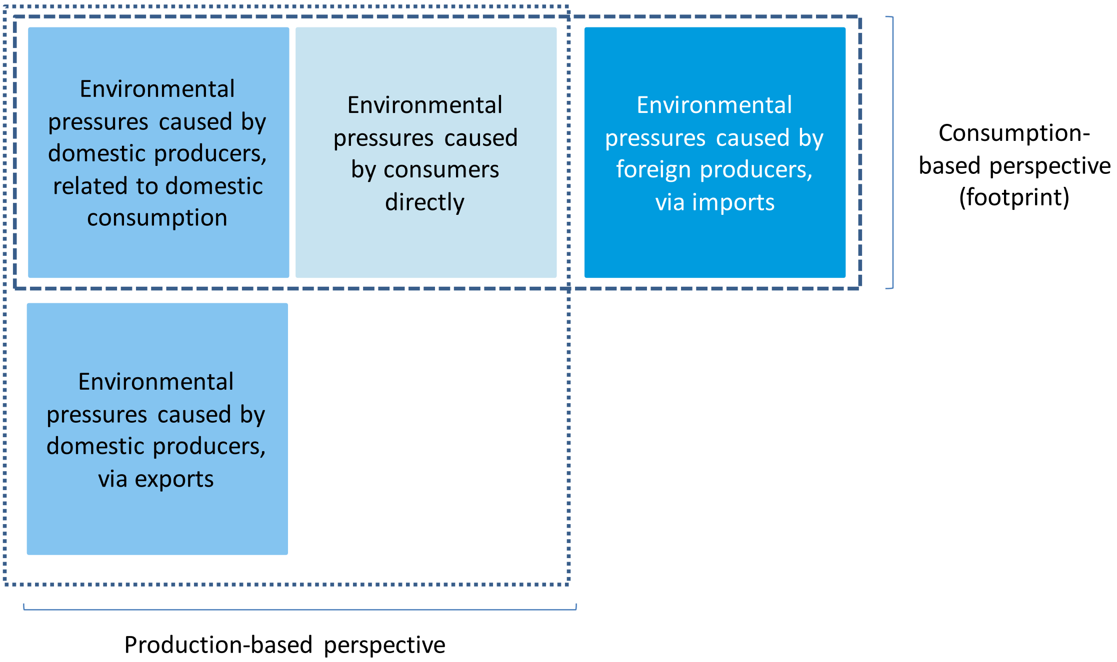
A country's environmental pressure can be measured from a production- or consumption-based perspective (Figure 3; Wilting and Ros, 2009). A production-based perspective relates environmental pressures or impacts to domestic actors responsible for causing these pressures, for national consumption and exports (e.g. agriculture, industry, manufacturing, transport, households). A consumption-based perspective, or footprint, refers to environmental pressures or impacts along the whole supply chain related to national consumption, including imports and excluding exports. Many of the current national policies and international agreements address environmental pressures within national borders, related to domestic production and direct consumption. A consumption or footprint perspective includes environmental impacts beyond national borders. Normative decisions relate to the environmental pressures that are taken into account when designing national targets and policies, either with respect to national territory or over the whole value chain, including pressures abroad (footprint).

A consumption-based perspective should not be seen as an alternative to a production-based perspective, but as a complimentary measure that provides additional information, including insights into international resource dependency and the contribution of consumption categories to environmental pressures. Furthermore, some studies argue that, compared to a production-based perspective, a consumption-based perspective provides a more equitable and correct picture of global environmental pressures and impacts (e.g. Wiedmann and Lenzen, 2018).

A production-based perspective slightly differs from a territorial perspective that refers to environmental pressures or impacts occurring within the territory of the country. The territorial perspective includes environmental pressures from foreign producers or consumers in the country. Contrary, the production-based perspective includes pressures from domestic actors that occur abroad, for instance from international transporters. Environmental policies are usually based on pressures from a territorial perspective.

Where production-based data are generally available from national statistics offices, consumption-based (footprint) data are more difficult to obtain, as this requires a quantitative assessment of the supply chains from primary production to final consumption, and the associated environmental pressures along these chains. Multi-Regional Input-Output (MRIO) models extended with environmental data are generally used to perform such assessments at the national level. MRIO models are based on MRIO tables that account for the monetary flows between economic sectors in and between multiple regions. These monetary flows are combined with the use of natural resources and environmental pressures, as associated with their production (using data from production-based accounts). This way MRIO analyses are used to assess the full linkages and supply chains between production and consumption of commodities, including all interim steps. Thus, embedded and indirect flows and use of certain resources and environmental pressures anywhere along the supply chain are inherent part of this method. The use of production-based data in the MRIO model assures that at the global level environmental pressures from a production perspective are equal to the pressures from a consumption perspective.

Figure 3
Accounting framework for environmental pressures and impacts



Source: PBL

Starting from the ecological footprint (Wackernagel and Rees, 1996) thinking has expanded significantly in the last two decades. Environmental footprints have been calculated at several levels, such as the national level, as in this study, but also for industries, companies or products. Consumption-based studies have been performed for all types of environmental extensions and resource use; for example, greenhouse gas emissions (Hertwich and Peters, 2009), land use (Weinzettel et al., 2013), material use (Wiedmann et al., 2015), water use (Lenzen et al., 2013), and nitrogen emissions (Oita et al., 2016). More recently, also human consumption was linked to global biodiversity loss, in studies on biodiversity footprints (Lenzen et al., 2012; Wilting et al., 2017). Wiedmann and Lenzen (2018) give an overview of recent studies on global environmental and social footprints.

2.3.3 Ethical considerations

As a global framework, the planetary boundaries make no distinction between resource use and resource requirements of different groups of people (Raworth, 2012). However, consumption of natural resources and related advantages and disadvantages are generally not equally distributed among countries and between groups of people. Countries differ:

1. in their stage of development. The least developed countries in general have much smaller per capita environmental footprints than high developed countries. Furthermore, improving the economic conditions and quality of life of the billions of people living in poverty today, inevitably comes with increasing demand for natural resources (e.g. land, water, energy).
2. with respect to the impact of global environmental change. Countries contributing the most to environmental degradation are generally not the countries that are confronted the worst negative impacts. A case in point are the local impacts of climate change, most severely felt in developing countries but primarily caused by historical greenhouse gas emissions elsewhere in the world.
3. in their ability to deal with environmental problems. Richer countries have more financial resource and a stronger knowledge base for both mitigation and adaptation.

When setting national targets, these differences between countries have implications for the issues of environmental justice, burden sharing, and allocation of scarce resources.

The idea of allocating resource rights or conservation duties among countries or people is not new. Common but differentiated responsibilities (CBDR) is a central principle in international environmental law, that is meant to represent the philosophical notions of fairness and equity in international policy (Pauw et al., 2014). It was formalised at the United Nations Conference on Environment and Development (UNCED, 1992) and reaffirmed in the 2030 Agenda for Sustainable Development (UN, 2015). The principle balances the need for all countries to take responsibility for global environmental problems, while recognising the wide differences between and variation in national circumstances and capacities.

The principle of CBDR is explicitly mentioned in Article 3 of the UN Framework Convention on Climate Change (UNFCCC, 1992). In the climate change context, the debate on CBDR addresses the distributive fairness in translating global emission reductions for climate change mitigation into national reduction targets (Metz et al., 2002). The principle of CBDR has also implicitly been acknowledged and manifested in other multilateral environmental agreements (Honkonen, 2009; Pauw et al., 2014), including the Convention on Biological Diversity (UNEP, 1992), the UN Convention to Combat Desertification (UNCCD, 1994), the Montreal Protocol on Substances that Deplete the Ozone Layer (UN, 1987) and the Convention on Long-Range Transboundary Air Pollution (CLTRAP, 1979).

In the climate change negotiations and literature, many proposals for fair and equitable sharing of emission reduction obligations have been proposed and discussed, based on a range of equity principles, including equality, responsibility, capability, right to development, cost-effectiveness and sovereignty (Fleurbaey et al., 2014; Höhne et al., 2014; Van den Berg et al., submitted):

- **Equality** refers to a common understanding in international law that each human being has equal moral worth and thus should have equal rights. In the climate change context, this is generally translated into all people having equal rights to use the atmosphere.

- **Responsibility** relates a country's relative contribution to environmental change to their level of responsibility for solving the problem. It relates to 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.
- **Capability**, also referred to as **capacity** or **ability to pay**, refers to the capacity of a country to contribute to solving environmental problems. In the climate change context, 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.
- **Right to development**, also referred to as **needs**, refers to the interests of poor people and poor countries in having their basic needs being 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.
- **Cost-effectiveness** refers to taking action where this is most cost-effective. In the climate change context, this principle is for example translated into equal marginal costs.
- **Sovereignty**, also referred to as **acquired rights,** 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.

Different approaches have been used to calculate emissions allowances or required emission reduction targets of countries over time (e.g. BASIC experts, 2011; Höhne et al., 2014; Pan et al., 2014; Pan et al., 2017). Den Elzen et al. (2003) make a distinction between rights-based and duty-based approaches. Approaches based on equity principles such as equality and right to development establish a right to resource use, while approaches framed in terms of responsibility and capability establish a duty to contribute to mitigation. The method applied in such studies consists of two steps. In the first step, the global greenhouse gas emission level in a certain year or period is defined, which is consistent with meeting a long-term climate objective, for example, limiting global mean temperature increase to 2 °C or less, with a likely probability. In the second step, different approaches are used for allocating efforts (total emissions or required emission reductions) to countries in that specific year or period (Höhne et al., 2014). More recently, a different strand of effort-sharing literature has started to focus on the direct allocation of carbon budgets (Raupach et al., 2014; Peters et al., 2015; Van den Berg et al., submitted). As there is a strong linear relationship between long-term temperature change and cumulative CO_2 emissions, it is possible to derive targets for cumulative CO_2 emissions tolerable over a certain period. Country-level budgets derived from the global budget have the advantage that countries can decide themselves on their own pathway given the allocated budget.

The challenge for policymaking is that not only different equity principles, but also different implementations of these equity principles into approaches can lead to very different outcomes (Höhne et al., 2014). Moreover, there is no global consensus on which equity principle should be leading in a global environmental regime. Under the Paris Agreement, national targets are based on individual country pledges. The same holds for the 2030 Agenda for Sustainable Development, where national SDG targets are to be determined by countries themselves, in line with the global ambition set out in the 2030 Agenda. What could be considered fair is a political decision. However, there is no global process that guarantees the global target will be achieved. The Emissions Gap Report (UNEP, 2017) annually reports on the 'gap' between the emission reductions necessary to achieve the globally agreed target and the likely emission reductions from full implementation of the Nationally Determined Contributions (NDCs). The report informs policymakers of a potential mismatch between globally agreed targets and their individual contributions combined. The report could be an example for monitoring progress with respect to other global environmental challenges.

The planetary boundaries framework provides new challenges for the application of the allocation principles compared to the climate change literature. A budget approach is more in line with the planetary boundaries literature, with the general difference that the climate change problem can be framed as restricting a cumulative budget whereas other planetary boundaries can be framed as restricting annual budgets (see Section 2.3.1). Furthermore, the planetary boundaries differ in terms of their current global biophysical status—i.e. transgressed or still in the safe zone. Finally, for planetary boundaries with annual budgets, the same budget is available each year, hence historic resource use does not interfere with future availability. Thus, different approaches may need to be applied for the different planetary boundaries. The processes with a global scope (i.e. climate change and ocean acidification) can be treated as global commons problems with global budgets diminishing over time. For these processes, in theory, all approaches could be relevant. For the spatially heterogeneous systemic processes (biosphere integrity, land-system change and biochemical flows) equitable allocation is less straightforward, as these processes cannot directly be treated as global commons from a biophysical perspective. However, when socio-economic aspects (international trade) are included, producers and consumers may share responsibility for local environmental degradation.

2.4 Lessons learned from previous translation studies

Several researchers have translated planetary boundaries into specific national or regional boundaries, i.e. for Sweden (Nykvist et al., 2013), South Africa (Cole et al., 2014), Switzerland (Dao et al., 2015; Dao et al., 2018), the EU (Hoff et al., 2014; Häyhä et al., 2018), two Chinese regions (Dearing et al., 2014) and all countries (O'Neill et al., 2018). The studies use different conceptual approaches, including top-down allocation, regional biophysical thresholds, national policy targets, and local resource availability and conditions.

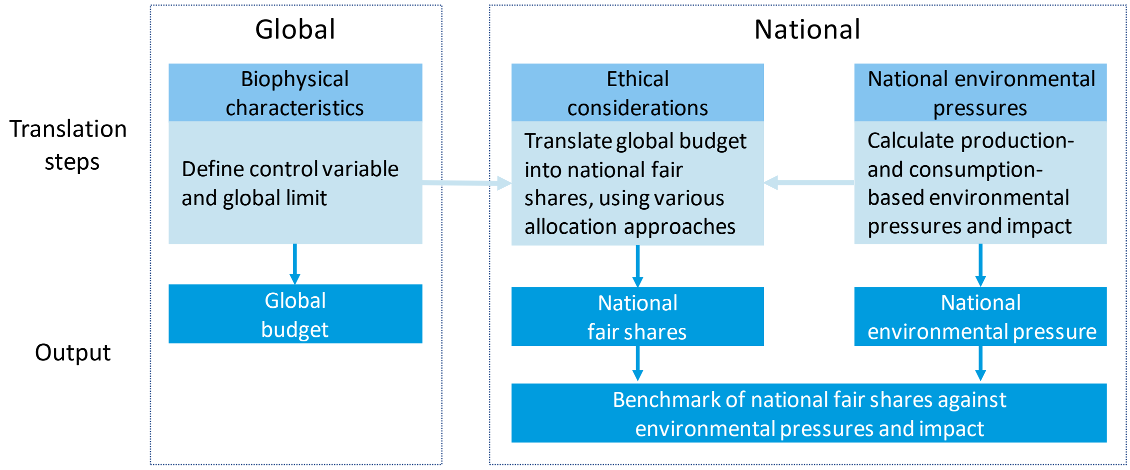
Häyhä et al. (2016) assess these studies in the light of their conceptual framework (Section 2.3). Most studies conclude environmental data as an important tool for national implementation, and data availability as an important factor determining the choice of the control variables. Defining precautionary boundaries to avoid local or regional environmental thresholds requires a different set of critical processes than the planetary boundaries. Studies using a top-down methodology are closely related to the planetary boundaries framework with respect to critical processes and control variables, take a production- and a consumption-based (footprint) perspective and explicitly address the ethical dimension. However, these studies only look at equal per capita allocation, based on current population numbers. The other, more bottom-up, methodologies relate more loosely to the planetary boundaries framework, take a territorial or production-based perspective and touch on equity mostly in the context of regional human well-being rather than intra-country inequality. The study by O'Brian (2018) looks at both human well-being and intra-country inequality by combining translated planetary boundaries with national poverty data.

From their analysis, Häyhä et al. (2016) conclude that future translation studies should:

- analyse the implications of alternative allocation approaches based on different equity principles;
- include a consumption-based (footprint) perspective;
- pay more attention to the temporal perspective, as both the individual planetary boundary processes and their interactions are dynamic.

In our analysis, we take the first two recommendations into account. We started by scaling global environmental limits, here defined by the planetary boundaries, to national budgets or targets (i.e. national fair shares), using a range of equity principles (Chapter 3). In a consecutive step, we calculated global, EU-level and national environmental pressures and related impacts from a production-based and a consumption-based (footprint) perspective (Chapter 4). In the final step, we used the calculated national fair shares as benchmarks for the national environmental pressures and impacts (Chapter 5). The steps are graphically represented in Figure 4.

Figure 4
Steps for translating global limits into national targets



Source: PBL; Adapted from Häyhä et al. (2016) and Hoff et al. (2017)

3 A safe operating space for the Netherlands

Current environmental footprints and future resource requirements differ significantly between countries. Furthermore, there are large differences in how countries are confronted with environmental change and their ability to deal with these global environmental challenges. Here we discuss the implications of different interpretations of fair and equitable distribution for defining 'national fair shares' of the global safe operating space for the Netherlands, i.e. a national Safe Operating Space.

3.1 Selected planetary boundaries and allocation approaches

For the translation of planetary boundaries into national budgets or targets, we used the framework developed by Häyhä et al. (2016), as described in Section 2.3. The framework was applied earlier to the EU level, in a study for the European Environment Agency (EEA) (Hoff et al., 2017; Häyhä et al., 2018). Our analysis focuses on the global systemic and cumulative processes. We put ozone depletion aside, as most ozone-depleting substances are currently being phased out. Furthermore, we also put ocean acidification aside, due to its almost one-to-one relationship with the climate change boundary. Overall, four planetary boundaries are selected for further analysis: climate change, land-system change (here interpreted as land-use change), biogeochemical flows (nitrogen and phosphorus) and biosphere integrity (here interpreted as biodiversity loss). These boundaries directly relate to SDG targets under SDG13 (climate change), SDG14 (ocean biodiversity) and SDG15 (terrestrial biodiversity). Control variables are selected at the level of drivers or pressures, where possible. Other selection criteria include the possibility to compute footprint indicators and their availability in model projections.

For climate change, the global limit is based on the Paris Agreement. For the other planetary boundaries, the respective global limits from the planetary boundaries framework are used. The limits are interpreted as global budgets, which, in a consecutive step, are allocated to countries on the basis of alternative allocation approaches. The global CO_2 budget is interpreted as a budget over time, i.e. total CO_2 emissions that could still be emitted worldwide in order to stay below a 1.5 °C increase. Current CO_2 emissions reduce what can be emitted in the future, resulting in a decreasing budget over time. For the other planetary boundaries, the budgets are interpreted as annual budgets (i.e. current use does not interfere with future availability). For example, if managed sustainably, total available cropland will remain constant over the years. Table 2 provides an overview of the selected planetary boundaries, control variables, global limits and whether a budget over time or annual budget approach is used for the allocation. Appendix A discusses the rationale behind these choices.

Table 2
Selected planetary boundaries, control variables and global limits

Planetary boundary		Control variable	Global limit	Budget
Climate change		CO_2 emissions	400 $GtCO_2$ [1]	Budget over time
Land-use change		Cropland used	15% [2]	Annual budget
Biogeochemical flows	**N**	Intentional N fixation	62 Tg N/yr [3]	Annual budget
	P	P fertiliser use	6.2 Tg P/yr [3]	Annual budget
Biodiversity loss		MSA loss [4]	28% [5]	Annual budget

[1] Remaining global CO_2 budget for staying below 1.5 °C warming (>50% chance) from 2015 onwards (IPCC, 2014; Van Vuuren et al., 2017a); [2] Percentage of global land cover converted to cropland. Based on Rockström et al. (2009). In calculations used as ha Cropland; [3] Based on Steffen et al. (2015b); [4] Mean Species Abundance (see Alkemade et al., 2009); [5] Based on a comparison between the BII and MSA (see Appendix A). In calculations used as ha MSA loss

Table 3
Different approaches used and their parametrisation

Approach	Equity principle	Rationale	Parameters	Settings [1]
Grandfathering (GF)	Sovereignty	Allocation of budget based on share in global environmental pressure	Resource use	Production, **consumption**
Immediate equal per capita allocation (IEPC)	Equality	Allocation of budget based on share in global population	Year of population share	**2010,** 2030, 2050, 2100
			Population projection	SSP1, **SSP2**, SSP3 [3]
Equal cumulative per capita allocation (ECPC)	Equality	Similar to IEPC, but based on cumulative population share, since 2010	End year of cumulation	2030, **2050**, 2100
			Population projection	SSP1, **SSP2**, SSP3 [3]
Ability to pay (AP)	Capability	Allocation of relative reduction based on GDP per capita, relative to other countries	Resource use	Production, **consumption**
			Year of GDP share	**2010,** 2030, 2050, 2100
			GDP metric	MER, **PPP** [2]
			GDP projection	SSP1, **SSP2**, SSP3 [3]
Development Rights (DR)	Capability	Allocation of global reduction based on GDP per capita, and income distribution	Resource use	Production, **consumption**
Resource efficiency (RE)	Efficiency	Allocation of reductions to where the largest efficiency gains can be expected.	Resource use	Production, **consumption**

[1] Settings in bold are default settings; [2] MER = Market Exchange Rate; PPP = Purchasing Power Parity rate; [3] Population and GDP projections are taken from the shared Socioeconomic Pathways (SSPs). See Box 1 for details.

Box 1: Shared Socio-economic pathways (SSPs)

The SSPs are a set of five storylines on possible trajectories for human development and global environmental change during the 21st century (Riahi et al., 2017; Van Vuuren et al., 2017b). Each SSPs is described by a quantification of future developments in population (KC and Lutz, 2017), urbanization (Jiang and O'Neill, 2017) and economic development (Dellink et al., 2017); Van den Berg et al. (submitted), and by a descriptive storyline to guide further model parametrization (O'Neill et al., 2017). In our analysis, we use SSP1-3, with SSP2 being our default middle-of-the-road projection.

SSP1 (Sustainability) A world that makes relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Educational and health investments accelerating the demographic transition, leading to relatively low mortality. Economic development is high and population growth is low.

SSP2 (Middle of the Road) A world in which trends typical of recent decades continue (business as usual), with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. Fertility and mortality are intermediate and also population growth and economic development are intermediate.

SSP3 (Regional Rivalry) A world that is fragmented, characterized by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. The emphasis is on security at the expense of international development. Mortality is high everywhere, while fertility is low in rich OECD countries and high in most other countries. Economic development is low and population growth is high.

While for climate change many proposals for fair and equitable burden sharing (i.e. sharing of emission reduction obligations) have been presented and discussed in the literature, for the other three boundaries only a few studies discuss budget allocation, with most applying only one approach, i.e. per capita allocation (Häyhä et al., 2018; O'Neill et al., 2018). Here, building on the broad knowledge base in the climate change literature, we discuss national allocation results resulting from a range of allocation approaches, building on approaches applied in Van den Berg et al. (submitted). Six different approaches for allocating the global Safe Operating Space are selected, that span the space of different equity principles (see Appendix B for the formula used). Furthermore, for several approaches different parameter settings are possible (Table 3).

The **Grandfathering (GF)** approach is based on the sovereignty principle. The global budget is distributed according to the current share of a country's environmental pressure or impact. Current environmental pressure or impact can either be based a country's footprint or territorial resource use. We use this footprint as a default.

The **Immediate equal per capita allocation (IEPC)** approach is based on the equality principle. The global budget is distributed according to a country's share in the global population. This approach is used by most planetary boundaries translation exercises in the literature (Häyhä et al., 2018; O'Neill et al., 2018). Next to current population shares, we also assess the impact of future population dynamics, by using projected population shares in 2030 2050 ad 2100. For future population developments, population projections from the SSPs are used (see Box 1).

The **Equal cumulative per capita allocation (ECPC)** approach is based the equality and basic needs principles. Similar to IEPC, the approach underlines that all humans have equal claim to global collective goods, while at the same time taking future generations (and their needs) into account. The global budget is allocated according to a country's cumulative population share over a certain period. We use the 2010–2050 period as a default, while also looking at the 2010–2030 and 2010–2100 periods. For future population projections, the assumptions used are similar to those used for the IEPC approach.

The **Ability to pay (AP)** approach is based on the capability principle. For this approach, not the global budget, but the global reduction objective is distributed among countries.[4] The approach is therefore only applicable for planetary boundaries that are already transgressed, i.e. climate change, biogeochemical flows (nitrogen and phosphorus) and biodiversity loss. Global reductions are allocated to countries based on per capita GDP levels.[5] National shares of the global budget are calculated as the difference between current environmental pressure (footprint or territorial resource use) and their calculated reduction objective. We use a country's footprint as a default. Furthermore, we use 2010 as the default year for per-capita GDP levels, while also looking at 2030 and 2050 and 2100. For future GDP projections, the SSPs are used, similar to those used for the IEPC approach. Finally, we use GDP based on purchasing power parity (PPP) as default, while also looking market exchange rates (MER).

The **Development Rights (DR)** approach is also based on the capability principle. It builds on the Responsibility Capacity Index (RCI) of *Greenhouse Development Rights* (Baer et al., 2008), an approach that allocates greenhouse gas emissions on the basis of quantified capacity (GDP per capita and income distribution) and responsibility (contribution to climate change). Here, only the capacity term is used. Similar to AP, not the global budget, but the global reduction requirement is allocated. However, in contrast to Ability to pay, this approach allocates the absolute reduction objective. We use a country's footprint as a default to calculate national shares of the global budget.

The **Resource efficiency (RE)** approach is a different interpretation of the cost-effectiveness principle and is based on the efficient use of natural resources. It allocates the global budget based on equal resource efficiency. The efficiency parameter used depends on the planetary boundary. The approach is only applied to biogeochemical flows (nitrogen and phosphorus). The efficiency parameter is N/ha and P/ha of cropland. Cropland used can either be based on a country's footprint or its territorial resource use. We use the footprint as a default.

[4] The global reduction objective is the difference between current global environmental pressure or impact and the global limit (here interpreted as a budget).
[5] To take into account increasing marginal costs with steeper reductions efforts, the cube root of per capita GDP is used in the calculations (Van den Berg et al., submitted)

3.2 Allocation results across countries

Figure 5 shows allocated shares of the global budget for the EU, United States, India, China and the rest of the world, for the four planetary boundaries analysed and the six allocation approaches, using default settings. The selection covers the four largest economies and together account for almost 2/3 of the global population. It is based on the country grouping of the footprint calculations (see Table A1). Preferably, also Sub-Saharan Africa was included in the analysis, to provide insights into distributive choices on low income countries. However, this was not possible with the country grouping of the footprint calculations.

The various allocation approaches result in large differences between allocation results for countries and planetary boundaries. Translation of global budgets into national budgets or targets, essentially, divides up global resource budgets or reduction objectives. Approaches that allow higher environmental pressures or impact for one country, inevitably allow less for other countries.

Grandfathering based on current environmental footprints leads to relatively high shares for the EU and the United States, compared to the other approaches, and much lower shares for India. Current environmental footprints of the EU and the United States are high compared to those of developing countries. In essence, this approach constitutes an equal reduction objective between countries.

Equal per capita allocation divides the global budgets according to a country's population share. Compared to their current share in global environmental pressures and footprints, the approach allows lower shares for the EU and the United States and higher shares for India. Only for phosphorus fertiliser use the Indian share is slightly lower as current per capita use is relatively high. China's per capita environmental pressure for CO_2, phosphorus fertiliser use and intentional nitrogen fixation are around the global average, concluding similar shares for *equal per capita allocation* as for *grandfathering*.

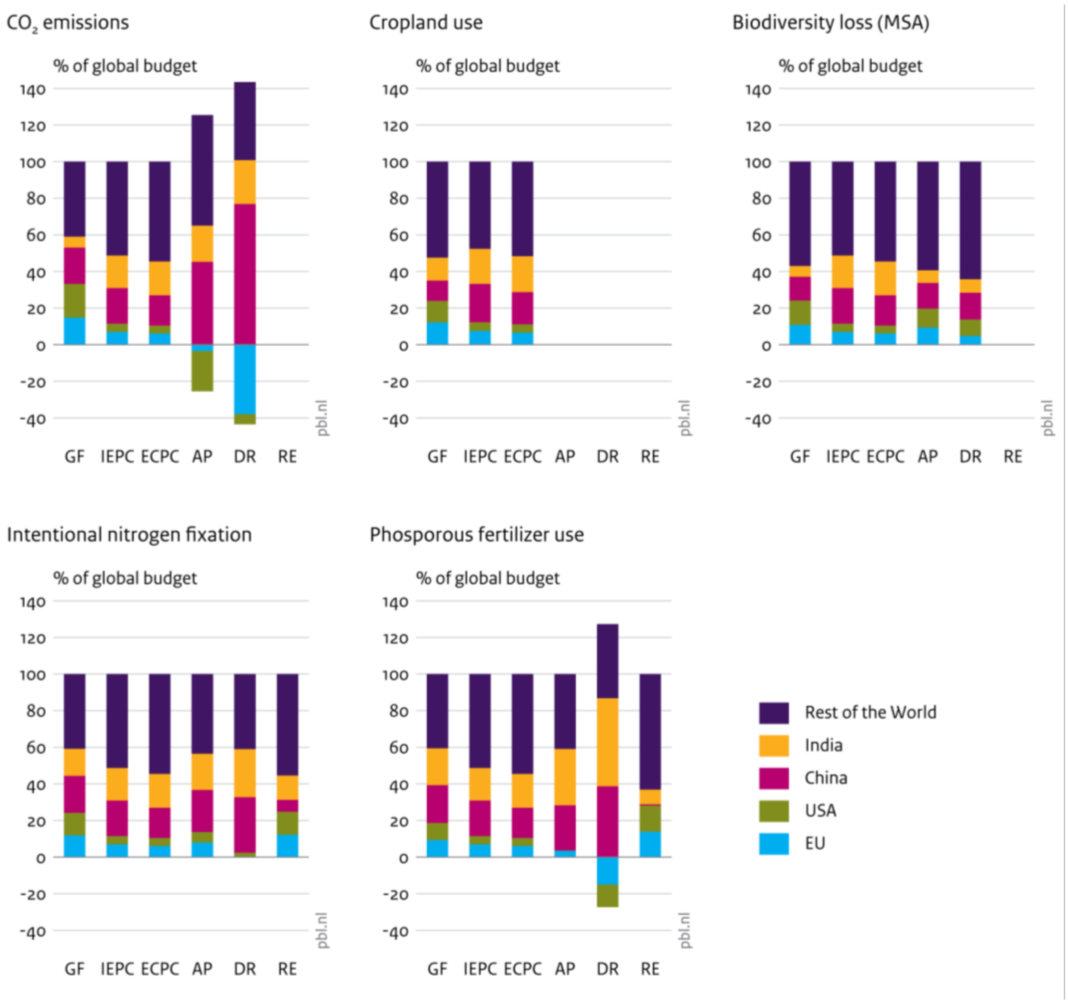
Cumulative equal per capita allocation leads to slightly lower shares for the EU and the United States than *equal per capita allocation*, as many developing countries have much higher projected population growth. For China this also leads to lower shares as its population is projected to decrease in the futures. In contrast, the approach allows higher shares for India.

Ability to pay results in relatively low allocation results for the EU and the United States compared to the other approaches. The approach allocates the relative global reduction objective. With intentional nitrogen fixation and biodiversity loss much closer to the global boundary than in the case for CO_2 emissions and phosphorus fertiliser use, their reduction objectives are much lower, resulting in higher shares. For CO_2 emissions this approach results in negative shares. In contrast, the approach results in high shares for China and India, as the result of much lower GDP per capita levels.

Box 2: EU results from the literature for the climate change boundary

Studies discussing regional emissions-reduction pathways in line with the 2 degrees climate target, conclude that by 2030 the EU will need to reduce its total greenhouse gas emissions by between 35% and 76% below 1990 levels (Van Vuuren et al., 2017a). For comparison, the current EU targets for 2030 is 40% reduction in total greenhouse gas emissions below 1990 levels. Studies that address climate change from a budget approach do not provide emission targets for specific years, but allocate the remaining carbon budgets directly, with countries deciding themselves how to distribute this over time. To compare such budgets to current performance (footprint indicators) the budget is generally spread equally over the remaining years this century. The planetary boundaries literature sofar only applied equal per capita allocation, concluding annual budgets of 1.6–2.0 t CO_2 cap^{-1} yr^{-1} (Häyhä et al., 2018; O'Neill et al., 2018). Van den Berg et al. (submitted) applied a broad range of approaches, concluding annual budgets for the EU of -8.6–2.9 t CO_2 cap^{-1} yr^{-1}. These studies calculate budgets in line with the 2 degrees target. Our calculations in this study, calculating budgets in line with the 1.5 degrees target, lead to lower annual budgets for the EU of -3.9–1.4 t CO_2 cap^{-1} yr^{-1}.

Figure 5
National and regional shares for the various allocation approaches



GF = Grandfathering; IEPC = Immediate equal per capita allocation; ECPC = Equal cumulative per capita allocation; AP = Ability to pay; DR = Development rights; RE = Resource efficiency

Development right is a specific case of *Ability to pay,* allocating the absolute instead of the relative reduction objective. Due to their high GDP per capita, this approach concludes very low to negative shares for the EU and the United States. In contrast, the approach concludes the highest shares for China and India of all approaches.

Resource efficiency allocates the global budget equally over current global cropland use (footprint-based). The approach is only applied to the biogeochemical flows boundary (nitrogen and phosphorus). With a large cropland footprint, the approach concludes the highest shares for the EU and the United States of all approaches. For China and India this approach results in the lowest shares. The approach benefits countries with high cropland footprints and relatively low fertiliser use per hectare.

It should be noted that approaches that allocate a global reduction objective (*Ability to pay* and *Development Rights*) can lead to negative shares when the absolute reduction target is higher than current environmental pressures or impact. Negative emissions are common for climate change mitigation, as there is a range of negative emission technologies (e.g. biofuels combined with carbon capture and storage, and reforestation) and emission trading schemes between countries. This is not directly the case for the other planetary boundaries. For example, certain resources, such as land and fertiliser use with nitrogen and phosphorus, remain essential for agricultural production and cannot easily be compensated. However, negative resource use can result from restoration projects or environmental offsetting (i.e. compensation for environmental impacts with equivalent benefits generated elsewhere). Introducing some sort of trading scheme could allow investments in efficiency gains or restoration projects to counterbalance national environmental pressures.

3.3 Allocation results for the Netherlands

The various allocation approaches and different parametrisation result in a large range of allocation results for the Netherlands for the different planetary boundaries. Table 4 shows national allocation results as per capita values for the Netherlands for the selected planetary boundaries and the six allocation approaches. The numbers between brackets are the range resulting from the different parameter settings (see Table 3). Except for the two *Equal per capita allocation* approaches, most approaches use current environmental pressures or impacts in their calculations, either as a basis to determine resource rights (i.e. *Grandfathering* and *Resource Efficiency*) or to determine the reduction objective (*Ability to Pay* and *Development Rights*). The results per allocation approach in Table 4 are founded on consumption-based pressures or impacts (footprint). For allocation results founded on production-based pressures or impacts, only the range over the approaches (default settings) are given.

Grandfathering and *Resource efficiency* based on current environmental footprint leads to relatively high allocation results for the Netherlands, compared to the global average. In essence, *Grandfathering* constitutes an equal reduction objective between countries, making it more difficult for developing countries to accommodate the projected future population numbers and economic growth without significant improvements in resource efficiency. Because of a large cropland footprint, *Resource efficiency* leads to the highest allocation for the Netherlands of all approaches. The two equal per capita allocation approaches show intermedia results.

By definition, *Equal per-capita allocation* leads to per-capita results that are similar to the global average. *Cumulative equal per-capita allocation* (also accounting for projected future population growth) produces slightly lower results, as many developing countries have much higher projected population growth than the Netherlands.

As a result of relatively high GDP per capita*, Ability to pay* and *Development rights* results in relatively low per capita allocation results for the Netherlands compared to the global average, and lead to negative results for some boundaries and parametrisations. Especially *Development Rights* results in negative results as the approach allocates the absolute global reduction objective.

The parametrisation of the different approaches does matter, although much more for *Grandfathering* and *Ability to pay* than for the two per capita approaches. The SSP1 scenario shows low population growth and high economic growth all over the world, while in SSP3 population growth is high and economic growth is low. High population growth outside the Netherlands results in lower allocation results when accounting for this growth. Using future estimates of GDP per capita, leads to higher allocation results, as most low- and medium-income countries are projected to have much higher economic growth and can therefore contribute more in the future, from a capability perspective. Furthermore, using GDP per capita in Market Exchange Rates (MER) instead of Purchasing Power Parity (PPP) concludes lower shares for the Netherlands as the income differences with developing countries is much higher under this assumption. Finally, allocation results based on production-based environmental pressure are much lower for most planetary boundaries then when using the environmental footprint (see Section 4.2).

The results clearly show that a national safe operating space cannot be defined uniquely. Overall, differences resulting from the various approaches relate to the underlying equity principle (e.g. sovereignty, equity, capacity), whether and how future generations and economic developments are taken into account (e.g. using 2030 population numbers instead of those of 2010) and if an approach shares the global resource space (grandfathering, per capita allocation and resource efficiency) or a reduction objective (ability to pay and development rights). Differences between countries relate to their current environmental pressures and their impact, current and future developments in population and income growth (e.g. using differing assumptions on future socio-economic developments), and current levels of resource efficiency. Differences between planetary boundaries depend on the level of global transgression of the respective boundary and, thus, on the available space for further increases in global environmental pressure (land-use change), or the required reduction in global pressure or impact (climate change, biogeochemical flows and biodiversity loss).

Table 4
Per capita allocation results for the Netherlands

	CO_2 emissions (tCO_2/cap)	Cropland use (ha/cap)	Intentional nitrogen fixation (kgN/cap)	Phosphorus fertiliser use (kgP/cap)	Biodiversity loss (MSA) (ha/cap)
The Netherlands					
Consumption-based					
Grandfathering	1.9	0.5	16.8	1.4	0.9
Equal per capita	0.7 [0.5–0.7]	0.3 [0.2–0.3]	9.0 [5.9–9]	0.9 [0.6–0.9]	0.5 [0.4–0.5]
Cumulative equal per capita	0.6 [0.6–0.6]	0.3 [0.2–0.3]	8.1 [7.3–8.5]	0.8 [0.7–0.8]	0.5 [0.4–0.5]
Ability to pay	-1.7 [-3.1–0.9]		9 [5.4–14.3]	0.2 [-0.4–1]	0.8 [0.7–0.9]
Development rights	-6.6		-10.8	-3.7	0.1
Resource efficiency			19.3	2.2	
Full range	-6.6–1.9	0.1–0.5	-10.8–19.3	-3.7–2.2	0.1–0.9
Production-based					
Full range	-6.8–1.9	0.1–0.5	-30.0–9.0	-6.6–0.9	-0.5–0.5
Global average	0.7	0.3	9.0	0.9	0.5

See Box 1 for description of approaches. Not all approaches could be applied for all planetary boundaries. For several approaches different parameterisations are possible. The First value is based on default settings. Numbers between brackets is the range over the alternative settings.

4 Environmental pressures and impacts

Increasing global environmental pressures and related impact are the result of a growing population, economic development and changes in consumption patterns. Furthermore, as a result of international trade, production (and related environmental pressures and impacts) and consumption of goods and services increasingly happens at different locations. Here we discuss future trends in global environmental pressures, and environmental pressures related to production and consumption in the Netherlands and the EU. Furthermore, we provide a more in-depth analysis of the Dutch footprint, including past trends, consumption categories, producing sectors and regions of origin.

4.1 Future trends in global environmental pressures and impacts

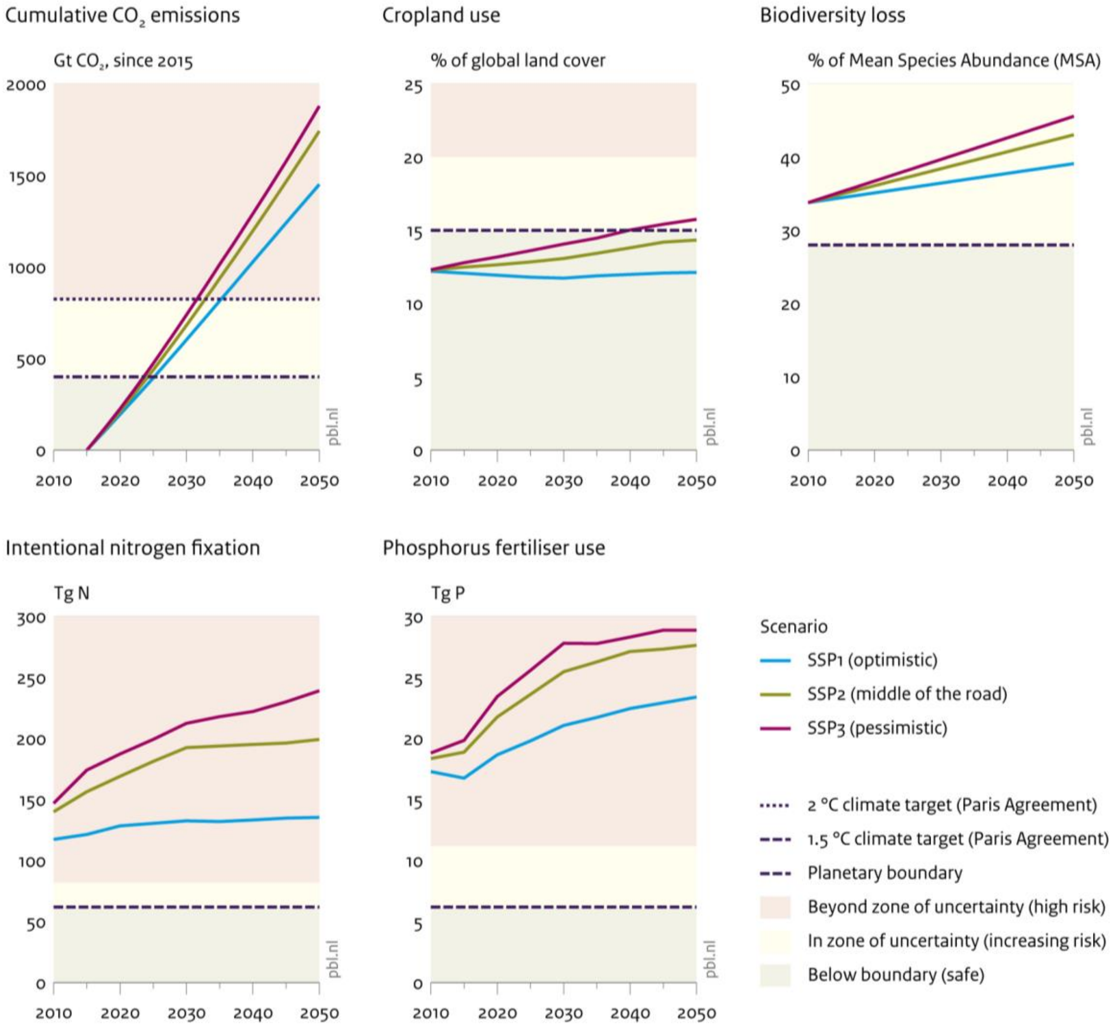
Four of the nine planetary boundaries are transgressed already (Steffen et al., 2015b). Figure 6 shows future developments in the selected control variables under different future socio-economic developments (see Box 1). The selected control variable for climate change, land-use change and biodiversity loss are different than those identified by Steffen et al. (2015b) and thereby provide slightly different results (see Appendix A). The projections are based on the IMAGE implementation of the Shared Socioeconomic Pathways (SSPs) (Box 1; Van Vuuren et al., 2017b). Overall, the projections show increasing pressure on all planetary boundaries analysed, in particular for climate change and biogeochemical flows (nitrogen and phosphorus), while the land-use change boundary (based on cropland used) will only be transgressed under very pessimistic scenario assumptions.

For climate change, under current emission levels (40 GtCO_2/year) the global budget of 400 GtCO_2, consistent with the 1.5 degrees target, will already be exhausted in 10 years. Model projections show cumulative CO_2 emissions for the 2015–2100 period of 3200–5200 GtCO_2 (Van Vuuren et al., 2017c), overshooting the global budget by a factor of 8 to 13. The planetary boundary of 350 ppm, as defined by Rockström et al. (2009) and which has already been exceeded, is more stringent than the 1.5 °C target that still allows around 400 GtCO_2 emissions this century. Global CO_2 concentration levels are projected to increase from roughly 400 ppm in 2015 to 590–1040 ppm by 2100, significantly overshooting the planetary boundary of 350 ppm CO_2.

Land-use and land-cover changes started in prehistory as direct and indirect consequences of human actions to secure essential resources, primarily fertile land for agriculture. In 1700, an estimated 7% of the global land surface was under cultivation (cropland and grazing land) mainly in Europe, India and China, which increased to 37% in 2015 (Klein Goldewijk et al., 2017). In the same year, forests extend around 31% of the global land area (FAO, 2016) in comparison with an estimated pre-industrial state of 41% to 42% (IPCC, 2007). The loss of forested land as percentage of original forest cover is projected to increase further (Doelman et al., 2018), approaching and surpassing the high risk zone in SSP2 and SSP3, respectively (not in Figure 6). Only in the SSP1 scenario global forest cover is projected stay moreover constant. The selected control variable, cropland used as percentage total ice free area, shows a similar trend, but only in SSP3 the planetary boundary is transgressed (around 2040), while in the other two SSP scenarios global crop area stays within the safe zone.

For biogeochemical flows, both intentional nitrogen fixation and phosphorus fertiliser use are projected to increase. Current intentional nitrogen fixation is estimated around 116–127 Tg N yr^{-1}, which is significantly above the planetary boundary of 62 Tg N yr^{-1} (Bouwman et al., 2017). Future projections show a further increase in intentional nitrogen fixation in all three SSPs, increasing to 135–222 Tg N yr^{-1} in 2030 and 137–253 Tg N yr^{-1} in 2050 (Mogollón et al., 2018b). Current global fertiliser phosphorus application is estimated around 17–20 Tg P yr^{-1}, also significantly above the planetary boundary of 6.2 Tg P yr^{-1} (Bouwman et al., 2017). Future projections show a further increase in fertiliser phosphorus application in all three SSPs, increasing to 21–28 Tg P yr^{-1} in 2030 and 23–29 Tg P yr^{-1} in 2050 (Mogollón et al., 2018a).

Figure 6
Future developments of control variables for selected planetary boundaries



Source: IMAGE

Projections are based on different future socio-economic developments (SSPs; Box 1). Sources: Climate change: Van Vuuren et al. (2017c); land-use change: Doelman et al. (2018); biogeochemical flows (nitrogen): Mogollón et al. (2018b); biogeochemical flows (phosphorus): Mogollón et al. (2018a); and biodiversity loss: Van der Esch et al. (2017).

Finally, current global biodiversity loss, measured as global loss in Mean Species Abundance (MSA), is estimated around 34%, which is above the boundary level of 28%. Projected global MSA loss reach values of 38% to 64% in 2050 (Van der Esch et al., 2017), further transgressing the global boundary. Due to large uncertainly zone of the boundary value, biodiversity loss does not reach the high-risk zone. Major causes of MSA loss are conversion of natural areas into agricultural land, forestry, climate change, encroachment from expanding human settlements, infrastructure and fragmentation.

4.2 Environmental pressures and impacts of the EU and the Netherlands

There are large differences between countries' environmental pressures and impacts. We use both production- and consumption-based (footprint) indicators for describing Dutch and EU performances on the individual planetary boundaries (Table 5 and Figure 7). The production-based indicators are purely based on environmental accounts and statistics. To calculate the consumption-based (footprint) indicators, a multi-regional input-output (MRIO) model was used that relates production and environmental pressures in one region via international trade flows to consumption (including by households, government and investments) in other regions (see Appendix C). At the global level, total environmental pressures and impacts are the same from both a production- and consumption-based perspective, but due to trade flows they differ at regional levels. Although the consumption-based indicators are more uncertain than the production-based indicators because of the additional modelling step, they still provide useful insights into the international resource dependency and the environmental pressures of main consumption categories.

With respect to climate change, between 1995 and 2010, the Dutch per capita CO_2 footprint remained moreover constant. Overall, global average CO_2 emissions in 2010 were around 4.4 tonnes per capita, which was about one third of the per capita footprint of the Netherlands and halve the per capita footprint of the EU. The difference between production and consumption-based CO_2 emissions in the Netherlands was small and almost constant over the 1995–2010 period. However, while the domestic share decreased between 1995 and 2010 with almost 10% and the EU share even with 25%, the non-EU share increased with more than 25%. This implies an externalisation of environmental pressure outside of the EU, especially to China.

For land-use change, global per-capita cropland use for Dutch consumption decreased slowly, starting in 2002, from 0.49 ha/cap in 2002 to 0.38 ha/cap in 2010. Still, in 2010, the Dutch cropland footprint was almost 20% higher than the EU average and almost double the global footprint. Since the Netherlands is relatively densely populated, the per-capita production-based cropland use in the Netherlands was four times lower than the global average. Also, in the EU, the consumption-based cropland use was higher than the production-based cropland use, reflecting the importance of imports for Dutch and EU consumption. Domestic share of the Dutch footprint is very small (around 1%), while around 80% is used in countries outside the EU. These shares have stayed moreover constant in the 1995–2010 period.

The nitrogen footprint (indicated by intentional nitrogen fixation) of Dutch consumers varied between 33 and 37 kg N per capita, over the 1995–2010 period. In 2010, the Dutch nitrogen footprint was almost 90% higher than the global average and almost twice as high than the production-based intentional N fixation in the Dutch agricultural sector. The domestic share decreased from 10% in the 1990s to 5% in 2010, due to a reduction in fertiliser use in Dutch agriculture. The share of EU countries also decreased in this period, concluding an externalisation of environmental pressure outside of the EU.

The phosphorus footprint (indicated by phosphorus fertiliser use) of Dutch consumers varied between 34 and 50 tonnes P per capita, over the 1995–2000 period, increasing until 2002 and decreasing after 2007 to around 36 tonnes P per capita in 2010. The domestic share in the phosphorus footprint was very small, starting from 5% in 1995 and decreased to around 2% in 2010. The EU share also decreases significantly during this period, concluding an externalisation of environmental pressure outside of the EU. In 2010, consumption-based phosphorus fertiliser use was about a factor four higher than production-based fertiliser use, comprising all phosphorus fertiliser use in the Dutch agricultural sector.

Table 5

Global, EU and Dutch per-capita resource use, in 2010

	CO_2 emissions (tCO_2/cap)	**Cropland use (ha/cap)**	**Intentional nitrogen fixation (kg N/cap)**	**Phosphorus fertiliser use (kg P/cap)**	**Biodiversity loss (MSA) (ha/cap)**
Global					
Total	4.4	0.20	17.4	2.3	0.77
EU					
Production-based	7.9	0.21	23.6	2.1	0.92
Consumption-based	9.5	0.32	30.0	3.1	1.21
Netherlands					
Production-based	12.2	0.05	13.4	0.8	0.74
Consumption-based	12.5	0.38	32.6	3.6	1.34

Figure 7
Environmental pressures and impacts, per capita, for the Netherlands

The per-capita biodiversity footprint of Dutch consumption remained moreover constant over the 1995–2010 period.[6] During the same period the domestic and EU share decreased, implying an externalisation of biodiversity loss for Dutch consumption outside the EU. In 2010, global biodiversity impact, measured in hectares MSA loss (MSA value times global ice-free land mass), was slightly below 0.8 ha/cap, similar to the production-based impact in the Netherlands. Dutch per-capita footprint, however, was almost twice this value. Also, in the EU, the consumption-based impact was higher than the production-based impact.

Overall, in 2010, with the exception of CO_2 emissions, Dutch consumption-based environmental pressures (footprints) are much larger than production-based environmental pressures. Furthermore, Dutch environmental footprints per capita are larger than the EU average and much larger than the global average. A large share of the environmental pressures beyond national borders relate to agricultural activities in other countries, including land use, nutrient pollution and biodiversity loss. Between 1995 and 2010, per capita environmental footprints of Dutch citizens remained moreover constant for CO_2 emissions, cropland area and MSA loss and decreased slightly for biogeochemical flows (N and P). During the same period, the share of environmental pressures and impacts abroad increased for most footprints. This indicates an externalisation of environmental pressure, meaning increasing environmental impacts linked to Dutch consumption outside the Netherlands.

[6] The calculated biodiversity footprint of Dutch consumption for the period 1995-2010 was limited to losses from greenhouse gas emissions and land use in agriculture and forestry, since for this period no data were available for the indirect impacts of land use on biodiversity.

4.3 Breakdown of Dutch environmental footprints

Footprint indicators depict total environmental pressures along the whole supply chains linked to consumption. Reducing environmental footprints requires options for both limiting the use of natural resources (reducing the size of the footprint) and for reducing the ecological impacts associated with the resource use (reducing the impact of the footprint) (Van Oorschot et al., 2013). Three categories of options can be identified: (1) reducing local environmental impacts of production; (2) more efficient production; and (3) making different choices in the consumption pattern. For environmental impacts abroad, this requires making international supply chains more sustainable.

To properly design such policies a breakdown of the footprint indicators in consumption categories, producing sectors and region of origin is required. Figure 8 provides an overview of sectors where environmental pressure or impact takes place linked to different consumption categories, for CO_2 emissions and biodiversity loss. Figure 9 provides an overview of regions where environmental pressure or impact takes place linked to different consumption categories, also for CO_2 emissions and biodiversity loss. For the other three environmental pressures (cropland use, intentional nitrogen fixation and phosphorus fertiliser use) see Appendix D. As these pressure are linked to the agriculture only, only the link to regions where pressures or impacts take place are presented.

The largest share (37%) of the Dutch CO_2 footprint originates in the energy sector. The energy sector is part of the supply chain of all consumption categories. Households cause about 20% of the CO_2 footprint directly by heating their houses (housing) and driving their cars (transport). The consumption categories with the highest CO_2 footprints are housing and services. The CO_2 footprint of housing comprises emissions related to heating, electricity use, and construction of houses (including concrete). Overall, 50% of the CO_2 emissions linked to Dutch consumption originate from domestic sources. Most CO_2 emissions related to housing and transport are domestic, while most CO_2 emissions related to goods and food are caused outside the EU.

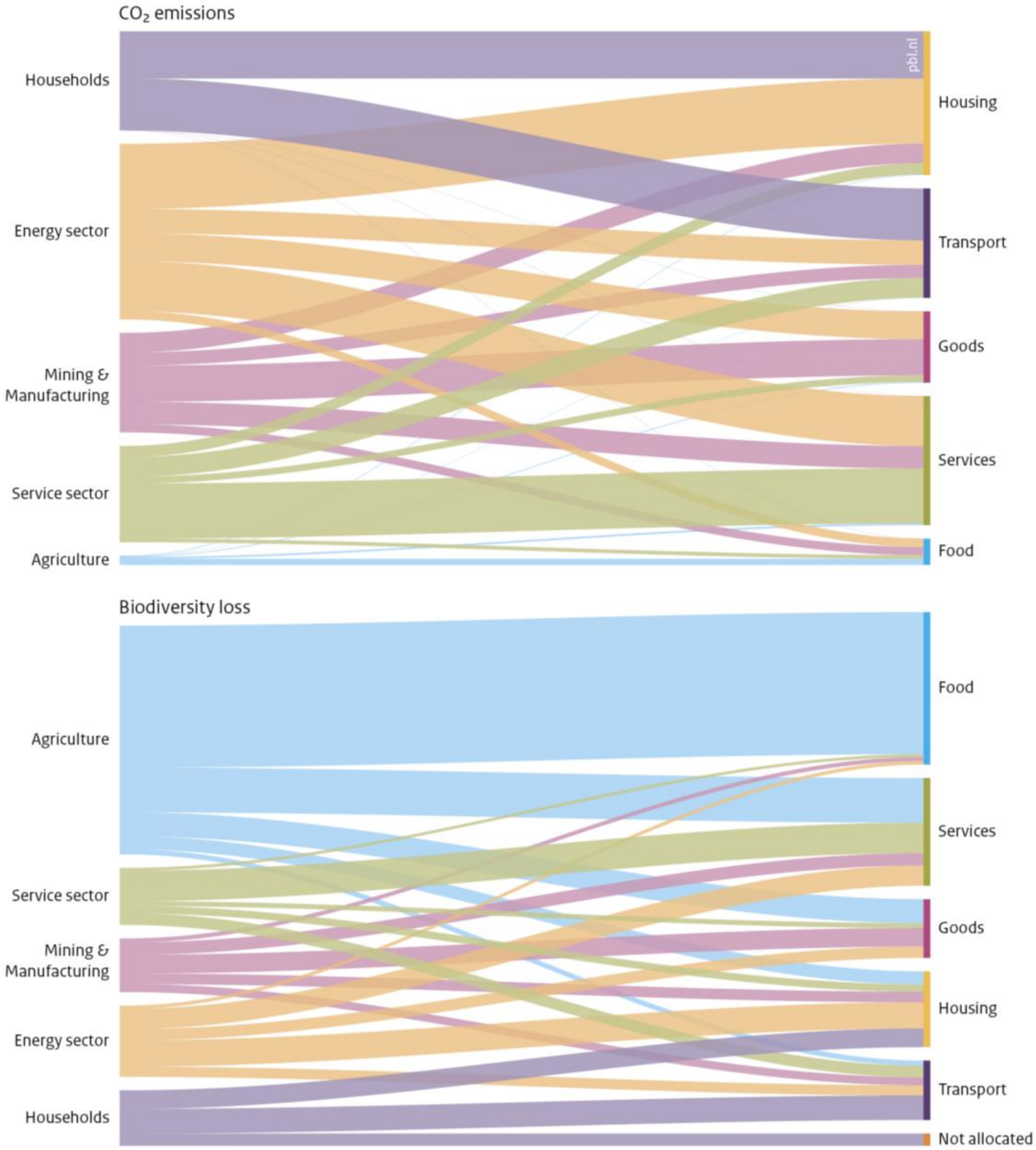
Cropland use is primarily linked to the agriculture sector. The consumption category with the highest cropland footprint is food. Other consumption categories that use cropland in their supply chains are services and to a lesser extent goods, housing and transport. The footprint of services comprises, among others, use of cropland for food in restaurants and healthcare institutions. Only a small share of the cropland footprint is in the Netherlands (1%–2%), while most cropland used for Dutch consumption is located in countries outside the EU.

Similar to cropland use, also the nutrient footprints (nitrogen and phosphorus) are primarily linked to the agriculture sector. Nitrogen fertiliser is applied on cropland and pasture land. Furthermore, crops, especially leguminous crops, bind the nitrogen from the air. Phosphorus is applied mostly on cropland. As a result, the consumption categories with the largest shares in the nitrogen and phosphorus footprints are similar to the categories identified in the cropland footprint. The same holds for the regional distribution, with 65% (nitrogen) and 75% (phosphorus) of the nutrient footprints originating outside the EU.

The largest share of the biodiversity footprint originates in the agriculture sector, while the consumption categories with the highest biodiversity footprint are food and services. Biodiversity loss from food consumption is caused by both greenhouse gas emissions and land use in agriculture. Impacts from pressures in other sectors are negligible in the biodiversity footprint of food. Biodiversity loss from services are induced in agriculture, but also by greenhouse gas emissions from other sectors. Biodiversity impacts from habitat replacement by built-up area and from encroachment were not allocated to specific consumption categories. A quarter of the Dutch biodiversity footprint was caused by greenhouse gas emissions and land-use impacts from economic activities in the Netherlands itself. From the foreign part of the footprint almost 80% was from biodiversity losses outside the EU. Especially agriculture-related impacts take place outside the Netherlands, while housing and transport related impacts are mostly domestically induced.

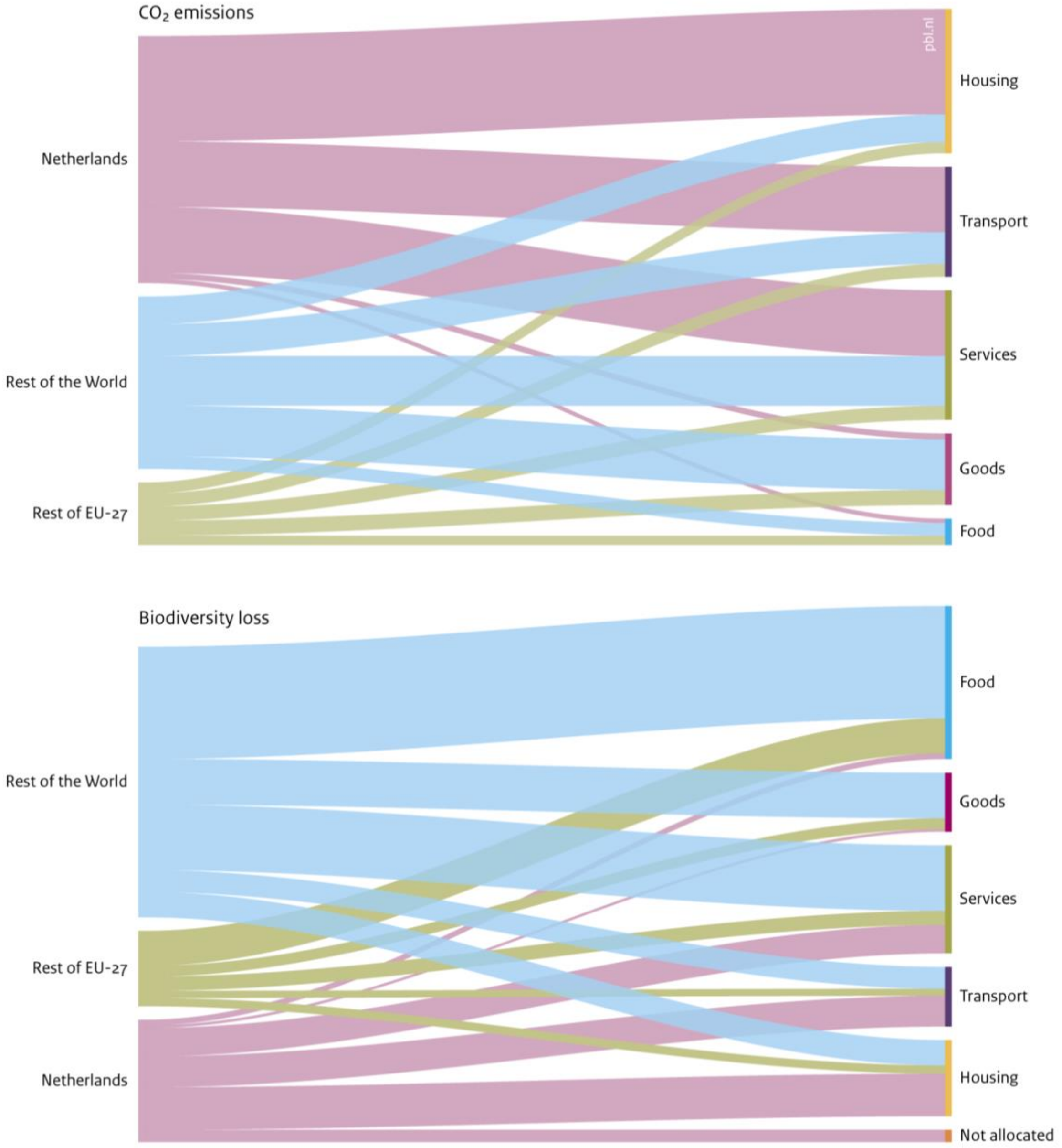
The breakdown of the footprint indicators in consumption categories, and producing sectors and regions showed that all types of policies are relevant. Further analysis is required in order to determine the optimal and most effective mix. Especially, Dutch food consumption has large environmental impacts outside the EU implying that trade and supply chain policies directed at agricultural products and options directed at changing diets might be the best options to reduce Dutch footprints for cropland and biochemical flows. Transfer of agricultural technologies is a promising approach to increase resource efficiency abroad.

Figure 8
Share of consumption categories (right) linked to the sectors where environmental pressure or impact takes place (left), 2010



Source: PBL

Figure 9
Share of consumption categories (right) linked to origin of production (left), 2010



Source: PBL

5 Policy implications

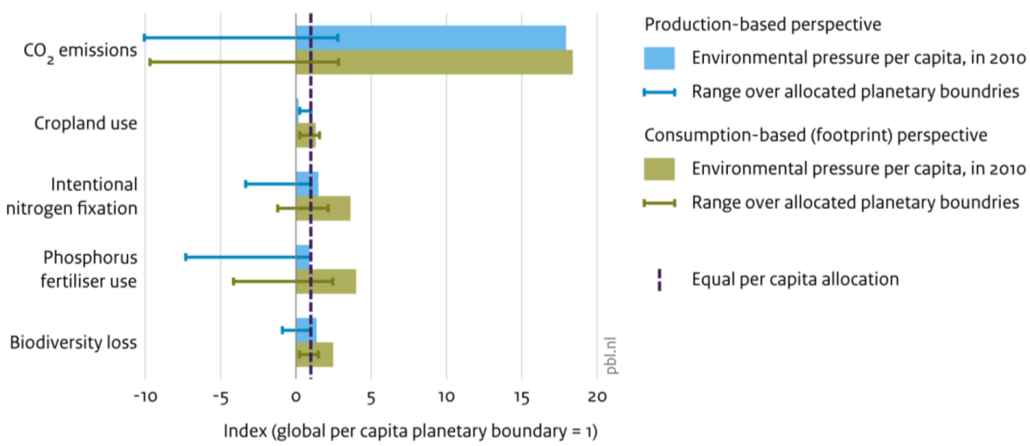
The preceding chapters discuss a methodology for translating global environment-related SDG targets into national policy targets, and the application of this methodology to the Netherlands. For the analysis, planetary boundaries were used as a set of science-based targets and various allocation approaches from the climate change literature to calculate national budgets or shares. Together, these budgets or shares could be interpreted as a 'national safe operating space'. This chapter assesses if the Netherlands is currently living within this national safe operating space, and discusses normative choices required for translating the global SDG ambitions into national levels as well as next steps in defining national SDG targets.

5.1 Global and national transgression of the safe operating space

To assess if the Netherlands is living within its safe operating space, we compares the translated planetary boundaries (Section 0) against Dutch national environmental pressures, both from a production-based perspective and a consumption-based perspective (Section 4.2). There are large differences in allocation results (national budgets or targets) for the various allocation approaches and planetary boundaries (Figure 10). Overall, except for the land-system-change boundary, all allocation results are lower than current Dutch environmental footprints. Compared to production-based environmental pressures, only the climate change boundary and, to a lesser extent, the biodiversity boundary are being transgressed under all approaches. Still, most allocation approaches conclude results that are lower than current production-based environmental pressures. From this can be concluded that, for most planetary boundaries and allocation approaches, the Netherlands is not living within its safe operating space.

The Dutch level of transgression differs significantly from the global level. Figure 11 compares global transgression with national transgression for the various planetary boundaries, distinguishing between clearly safe, safe, unsafe and clearly unsafe (see also Dao et al., 2015). This categorisation uses the ratio of 2010 environmental pressure or impact over the respective planetary boundary (global) or translated planetary boundary (national), based on *Immediate Equal Per Capita* allocation (dotted line in Figure 10).

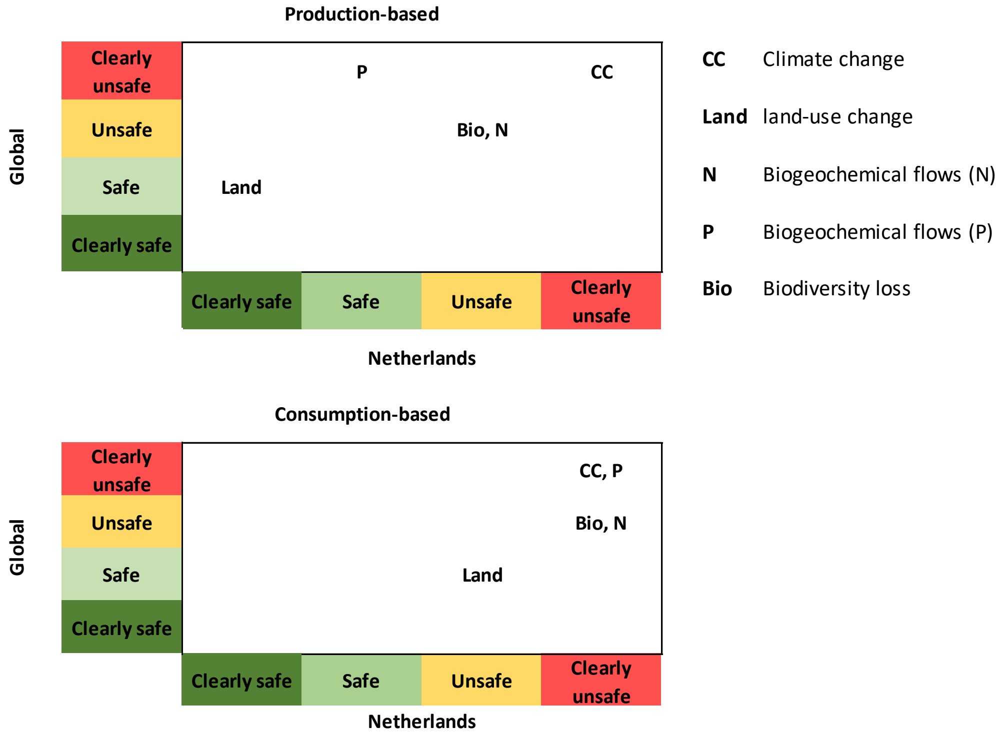
Figure 10
Dutch environmental pressures compared to allocated planetary boundaries



Source: PBL

Dutch environmental pressures and allocated planetary boundaries are scaled to the global per capita planetary boundary. As the climate change budget is a budget over time (see Section 2.3.1), the allocated budget is equally distributed over the remaining years of the 21st century.

Figure 11
Global and Dutch performance on planetary boundaries



Source: PBL

Categorisation is based the ratio of environmental pressure over the planetary boundary (global) and translated planetary boundaries using Immediate Equal Per Capita allocation (Netherlands), distinguishing 'clearly safe' (ratio below 0.5) 'safe' (ratio between 0.5 and 1), 'unsafe' (ratio between 1 and 2) and 'clearly unsafe' (ratio above 2). Based on Dao et al. (2015)

Of the five planetary boundaries, four are transgressed globally, with the biogeochemical flows (nitrogen) and biodiversity loss boundaries being 'unsafe' and the climate change and biogeochemical flows (phosphorus) boundaries being 'clearly unsafe'. The difference between the assessment of Steffen et al. (2015b) and our calculations for climate change is that they look at the current state, while our translation methodology allocates a budget over time, thereby including future trends in the analysis. From a production-based perspective, only climate change is 'clearly unsafe' for the Netherlands, while biogeochemical flows (both phosphorus and nitrogen) and biodiversity loss are 'unsafe'. From a consumption based (footprint) perspective, all national boundaries are transgressed; the land-system-change boundary is 'unsafe, while the planetary boundaries are 'clearly unsafe'. The level of transgression, thus, largely depends on the environmental pressures that are taken into account, either with respect to national territory or over the whole value chain, including pressures abroad (footprint).

5.2 National policy targets in line with planetary boundaries

Differences between the translated planetary boundaries and current environmental pressures and impacts can help to define national policy targets or reduction objectives. Table 6 shows reduction objectives resulting from the various allocation approaches when using a consumption-based (footprint) perspective for current environmental pressures and impacts. The reduction values are a rough orientation of sustainable levels of resource consumption for countries from a scientific point of view. They are not meant as directly applicable political targets. Furthermore, the presented reduction objectives are not time-bound. Setting a target year is part of the political process. It defines the speed with which a country decides to move towards their safe operating space.

Table 6
Reduction percentage for the different planetary boundaries

	Netherlands (%)	EU (%)	US (%)	China (%)	India (%)	Global (%)
CO_2 emissions	85–113	85–104	85–118	65–87	49–85	85
Cropland use	-40–31	-40–19	-40–41	-180–-40	-134–-40	-40
Intentional N fixation	40–202	43–161	42–150	28–99	8–85	62
P fertiliser use	41–133	47–100	48–90	23–84	9–54	49
Biodiversity loss (MSA)	31–91	31–69	31–77	-3–31	-116–31	31

Range over the six allocation approaches, using default settings. Negative values represent growth instead of reduction

As concluded from the analysis in Chapter 3 and further discussed in Section 5.2, a range of normative choices need to be made and these choices play out differently between countries, resulting in diverging perceptions of fair and equitable distribution. For one country, *Immediate Equal Per Capita* allocation can be most favourable, while, for others, *Ability to pay* or *Resource efficiency* results in the lowest reduction objectives. Globally, the largest reduction objectives are concluded for CO_2 emissions, while for cropland use the planetary boundary is not reached yet. For the Netherlands (but also the EU and United States), the global reduction objective is generally the lower bound (only for nitrogen and phosphorus, the *resource efficiency* approach results in lower reductions), while for China and India this is generally the upper bound (with the exception again of nitrogen and phosphorus for the *resource efficiency* approach). These distributive differences should be taken into account when discussing national targets.

It should be noted that national allocation of the global 'safe operating space' is not a simple matter of sharing a global budget. Local conditions, including temporal variability, play a crucial role in determining the level of sustainable resource use or tolerable emission levels. A multi-scale systemic approach might therefore be required (Steffen and Stafford Smith, 2013). The methodology applied does not account for spatial heterogeneity that is inherent in most selected planetary boundary. Calculations are only straightforward for climate change, as this is a global problem caused by rather homogenous pressure (greenhouse gas emissions). For the other planetary boundaries, this is more difficult. For example, for cropland use, not only its availability varies greatly across the world, but also its quality is very heterogeneous distributed, significantly influencing how effective land can be used. Cropland use per capita in Australia is much higher than in Europe simply as a result of the lower land quality (Van Vuuren and Bouwman, 2005). The same holds for biogeochemical flows, where nitrogen and phosphorus fertiliser use is largely dependent on local requirements. Furthermore, not all budgets are per definition constant. For example, for cropland use, land degradation is a serious concern, while phosphorus accumulation in soils and water can remain an environmental concern, although global levels are being brought below planetary boundaries. Finally, biodiversity loss and related loss of ecosystem functions are not readily interchangeable, as is the case for CO_2 emissions, while local tipping points could make it difficult to restore biodiversity when moving back within the safe operating space. Although the allocated budget should thus be interpreted with care, the approach taken does provide relevant insights for national target setting that includes environmental impacts along the whole supply chain. This is especially the case for a country such as the Netherlands, with its small, open economy and large environmental footprint abroad.

5.3 Normative choices for translating global SDG ambitions into national policy targets

Setting global environmental limits and translating them into national policy targets is primarily a political process. Normative choices and decisions link to the different translation steps (see Section 2.3). This includes quantification of the global level of ambition of the environment-related SDG targets, different perspectives on distributive fairness and related implications on national allocation results, and overall country-level responsibility, i.e. territorial or for the whole value chain.

With respect to the biophysical characteristics, the normative decisions relate to the selection of global environmental challenges, related global targets, and indicators or control variables for tracking progress. The 2030 Agenda includes a range of global environmental challenges to which the global community committed. However, besides for climate change with the Paris Agreement, there are no globally agreed quantitative policy targets for these challenges. Although the planetary boundaries framework includes many of these challenges (see Section 2.2), it remains a scientific concept. Further operationalisation of environment-related SDGs at the global level, especially with respect to their ambition level, can further national target setting. This includes agreeing on global quantitative target and related indicators for tracking progress. The recently started discussions for a post-2020 Global Biodiversity Framework under the Convention of Biological Diversity (CBD) could further this discussion for biodiversity.

Translating global environmental targets into national policy targets involves integrating its global environmental perspective into national policy and decision-making processes. Normative decisions relate to the extent of what can be considered to be a fair and equitable distribution of global resource budgets or reduction objectives. There is no common accepted definition of fairness. We discussed allocation results based on a range of distinct equity principles that emerged primarily from the climate change negotiations and literature, including equality, capability, right to development, cost-effectiveness and sovereignty. Our analysis concludes that different interpretations of equity, translated into allocation approaches, can result in large differences of allocation results for individual countries. Approaches that allow higher environmental pressures for one country, inevitably allow less for other countries. For example, the calculations conclude relatively high allocation results for the Netherlands for approaches based on current global resource use or impacts (*Grandfathering*), and based on *Resource efficiency*), while low allocation results are concluded for approaches based on per capita income (*Ability to pay* and *Development Rights*). For developing countries like India this is the other way around. When designing national targets, these implications should be taken account.

Finally, with respect to national environmental pressures the normative decisions relate to overall responsibility that a country takes, i.e. territorial or over the whole value chain. Many of the current policies address environmental pressures within a country, related to production processes and direct consumption. A consumption-based perspective refers to environmental pressures or impacts along the whole supply chain related to national consumption, thereby including environmental pressures beyond national borders. Our analysis concludes that Dutch environmental footprints are significant. Per capita footprints of Dutch consumption are higher than the EU average and much higher than the global average. Furthermore, between 1995 and 2010, the national footprint beyond national borders increased. When designing national targets also these considerations should be taken into account.

5.4 Next steps in defining national SDG targets

The Dutch Government has clear ambitions on climate change, but is less clear about what it wants to achieve with the SDGs. The planetary boundaries framework provides an Earth system perspective on global environmental change that goes beyond climate change. The framework can support defining the 2030 Agenda's global ambition level for SDG targets that address other global environmental challenges, such as those linked to land-use change, biogeochemical flows (nitrogen and phosphorus) and biodiversity loss. Furthermore, setting national policy targets in line with the SDG ambitions can build on the experiences and insights from climate change negotiations and the literature. The developed methodology can inform the discussion about a post-2020 Global Biodiversity Framework that is currently being discussed under the Convention of Biological Diversity (CBD). Furthermore, the methodology can help setting targets for companies, similar to the Science-Based Targets initiative that allocates carbon budgets to companies in the context on the United Framework Convention on Climate Change (UNFCCC).

The analysis addresses the distributional implications of alternative allocation approaches based on different equity principles, and compares these results with current national environmental footprints. It thereby addresses two of the three recommendations of Häyhä et al. (2016). Future analysis should also pay attention to the spatial heterogeneity that is inherent in most selected planetary boundary. Furthermore, the temporal perspective of global environmental challenges is important to take into account, as both the individual planetary boundaries processes and their interactions are dynamic. Finally, many global environmental challenges are interrelated. For example, climate change, land-use change and nitrogen deposition all negatively impact biodiversity (Alkemade et al., 2009), while land-based climate mitigation (e.g. reforestation and the use of bio-energy) can negatively impact these boundary processes, as well (Heck et al., 2018). With respect to planetary boundaries, the dynamics of a boundary may thus depend on the transgression status of other boundaries and the way policies are designed to address their transgression. Future analysis should therefore also address the interrelations between global environmental challenges.

Based on scientific insights into planetary boundaries, distributive fairness and national footprints, our analysis concludes that the Netherlands is not living within its safe operating. Current Dutch environmental footprints are higher than allocated planetary boundaries based on different interpretation of fair and equitable distribution. However, the material footprint is the only footprint indicator that is officially listed in the global SDG indicator set (i.e. it monitors the progress towards SDG8 and SDG12 (UN, 2017a)). The second Dutch performance monitoring of the SDGs (CBS, 2018a) and the Monitor of Well-being (CBS, 2018b) both also include the carbon footprint. However, other global footprint indicators, including those on land use, intentional nitrogen fixation, phosphorus fertiliser use and biodiversity loss, are equally relevant. These footprint indicators should also be included in the national indicator sets, in order to monitor progress of global environmental pressures that are linked to Dutch consumption.

The scientific knowledge of global systemic risks is evolving at the same time as environmental pressures are intensifying, globally. Furthermore, operationalisation involves normative political decisions about fair and equitable distribution of the global safe operating space. Science can help setting global quantitative targets by providing insights into societal risks of different levels of global environmental change. Furthermore, science can help with translating these targets into national targets and policies, by systematically analysing the implications of alternative allocation approaches based on various interpretations of fair and equitable distribution. Global climate change negotiations have proven that such scientific knowledge and insights are invaluable for incorporating global environmental challenges into national policy-making.

Further operationalisation of SDGs that address global environmental challenges in the Netherlands requires more dialogue and closer cooperation between scientists and policymakers (Hoff et al., 2017). Cooperation could provide legitimacy and scientifically sound underpinning. When integrated in a global regime, operationalisation can help ensure that policy goals are coherent between scales. Attention is needed for the translation of global biophysical terms into usable measures of resource use, ecosystem effects and environmental quality standards. Furthermore, it is important to specify the overarching objective and clarify how the SDGs can add value to local-to-regional environmental management. Finally, it may be necessary to determine which global environmental change processes are most relevant or have the most leverage in specific contexts at the national scale.

Translated planetary boundaries can help defining national policy targets in the Netherlands in line with the global SDG ambition. Ongoing policy processes and new policy programmes may serve as entry points. This includes the Dutch Government-wide programme for a Circular Economy and discussions around a transition in food and agriculture. Furthermore, the knowledge gained is relevant in the context of the discussion in the Dutch Parliament about a broader definition of welfare ('Brede Welvaart') to assist the public and political debate on human well-being (see CBS, 2018b).

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Appendix A: Control variables and global limits

A.1 Climate change

Climate change is one of the first recognised and most emblematic planetary boundaries and has been defined as one of two core boundaries that are strongly interlinked with the other boundary processes (Steffen et al., 2015b). The prime cause of climate change is greenhouse gases emissions, in particular carbon dioxide, causing widespread impacts on human and natural systems (IPCC, 2014). The climate change boundary links to article 2 of the United Nations Framework Convention on Climate Change, i.e. 'prevent dangerous anthropogenic interference with the climate system', called for by the (UNFCCC, 1992). This includes, among others, minimising risks of regional climate disruptions through droughts, flood and other extreme events, reduction of land glaciers mass and related threat to water supply, a rapid retreat of arctic sea ice and related sea level rise, and a shift in biodiversity and agriculture (IPCC, 2014). Climate change is a global issue since its main pressures, greenhouse gas emissions, are accumulating in the atmosphere independent of their location of origin. The boundary process or its main pressures, directly impact a range of other boundary processes, including ocean acidification, ozone depletion, biosphere integrity and freshwater use.

The climate change boundary is defined in terms of atmospheric CO_2 concentration and change in radiative forcing (Steffen et al., 2015b), while current global policy targets are expressed in terms of maximum allowable global temperature increase (UNFCCC, 2015). In practice, a temperature target or CO_2 concentration or radiative forcing targets are useful operational measures. As cumulative CO_2 emissions strongly determine the overall warming impact on a century timescale, it is possible to determine carbon budgets consistent with different temperature targets (Meinshausen et al., 2009; Friedlingstein et al., 2014; IPCC, 2014). The carbon budget is the maximum amount of CO_2 emissions that could still be emitted worldwide in order to stay below a specific temperature target. Here, we use CO_2 emissions (Gt CO_2 per year) as control variable.

The current global climate target is that of 'Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels' (UNFCCC, 2015). We use a remaining global CO_2 budget of 840 [590–1240] Gt CO_2 for staying below 2 °C warming (>66% chance) and 400 [390–440] Gt CO_2 for staying below 1.5 °C (>50% chance), both from 2015 onwards (IPCC, 2014; Van Vuuren et al., 2017a).

A.2 Land-use change

The land-system change boundary focuses on changes in land use. These changes are primarily driven by agricultural expansion and demand for forest resources, causing changes in energy and water fluxes, impacting the climate system and the hydrological cycle, as well as threatening biodiversity, biosphere intactness and ecosystem functions, with the risk of undermining human well-being and long-term sustainability (Foley et al., 2005; MA, 2005). Land-system change is usually considered a regional issue rather than a global one, since changes occur at sub-global scales. A global perspective can however be adopted when considering how land-cover changes affect the global Earth system, in particular through the impact on climate change (lost carbon sequestration, CO_2 emissions from deforestation and surface albedo) and global biodiversity loss (habitat loss and fragmentation). Furthermore, land scarcity and degradation can push agriculture into marginal lands with lower yields and higher degradation risks, with potential further degradation and expansion as a result.

Rockström et al. (2009) used the percentage of global land cover converted to cropland as control variable, thereby focusing on biodiversity protection and ecosystem functioning. Steffen et al. (2015b) used the area of forested land as percentage of original forest cover, thereby shifting the focus towards the biophysical processes in the land system that directly regulate climate (i.e., exchange of energy, water, and momentum between land surface and the atmosphere). For the sake of data availability, especially with respect to footprint data, we use the definition of Rockström et al. (2009).

The global boundary value was set at maximum 15% of global land cover converted to cropland, with an uncertainty zone of 15% to 20%. Here, we use the same boundary value and uncertainty zone.

A.3 Biogeochemical flows: nitrogen

The biogeochemical flows (nitrogen) boundary focuses on perturbations of the global nitrogen (N) cycle. Human fixation of atmospheric biologically unavailable nitrogen (N_2) into reactive compounds (N_2O, NO_x, NO_3-, NH_3 and NH_4) can cause eutrophication and acidification of terrestrial, freshwater and coastal ecosystems and related loss of biodiversity, climate change, stratospheric ozone depletion, air pollution and groundwater contamination (De Vries et al., 2013). The most important anthropogenic sources are agriculture (fertiliser application and crop fixation) and fossil fuel combustion. The planetary boundary focuses on avoidance of large-scale environmental impacts of excess nitrogen deposition, i.e. acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems. Although nitrogen impacts are usually considered regional rather than global issues, similar to the biosphere integrity and land-system-change boundaries, local and regional changes can cascade to global consequences by their relations with other planetary boundaries, namely land-system change, biosphere integrity, climate change, aerosol loading, ozone depletion, and indirectly freshwater use (affecting usable quality, rather than quantity). There are large differences between regions, with some having excess nutrient flows, while other are nutrient-deficient with negative impacts on agricultural productivity.

The anthropogenic increase in nitrogen fixation is not equally distributed across the globe. While some world regions, including large parts of Europe, suffer from excess release of nitrogen into the environment, other parts of the world suffer from suppressed agricultural yields and malnutrition that could be remedied by using increased nitrogen fertiliser use (Sutton et al., 2013). Even within Europe, there are large differences in nitrogen application, by a factor 10 and more (Leip et al., 2011) and also major differences in the sensitivity of receiving ecosystems (Hettelingh et al., 2008). Accordingly, it is difficult to set a strict and authoritative limit of ‘acceptable release’ of reactive nitrogen into the environment. Furthermore, different potential boundary values can be calculated, depending on what ecosystem thresholds or impacts are to be avoided, i.e. climate change, air pollution, eutrophication (De Vries et al., 2013).

The original Rockström et al. (2009) paper used the amount of N_2 removed from atmosphere for human use as control variable. In response, De Vries et al. (2013) argue that a planetary boundary for nitrogen should include adverse environmental impacts as well as the benefits of reactive nitrogen use (food security). Furthermore, they argue a clear difference between *intended* biological and chemical nitrogen fixation, mainly for the use of agriculture, and *unintended* nitrogen fixation, mainly from industry and transport. As they relate to different environmental problems, they cannot simply be added. For the nitrogen planetary boundary, Steffen et al. (2015b) focus on eutrophication of aquatic ecosystems and subsequently updated the control variable to nitrogen fixation in fertiliser production and from crop fixation. The boundary acts as a global ‘valve’ limiting the introduction of new reactive nitrogen to Earth system, while the regional distribution of nitrogen fertiliser is critical for impacts. We also use this indicator as control variable.

Taking into account critical limits for four major environmental concerns—air pollution, climate change, drinking water quality and eutrophication of aquatic ecosystems—the global nitrogen fixation planetary boundary should range between 20 and 133 Tg N yr^{-1}, while a rough estimate of 50–80 Tg N yr^{-1} is required for food security reasons (De Vries et al., 2013). Based on these insights and the focus on eutrophication of aquatic ecosystems, Steffen et al. (2015b) updated the planetary boundary to 62 Tg N yr^{-1}, with an uncertainty zone of 62–82 Tg N yr^{-1}. Here, we use the same boundary value and uncertainty zone.

A.4 Biogeochemical flows: phosphorus

The biogeochemical flows (phosphorus) boundary focuses on perturbations of the global phosphorus (P) cycle. Phosphorus is a critical factor for agricultural production. However, excessive phosphorus losses to aquatic ecosystems through runoff and erosion can cause the eutrophication of lakes and coastal systems. Furthermore, its inorganic form, used for chemical phosphorus-based fertilisers, is a non-renewable resource and thereby a key concern as there are no substitutes. Main anthropogenic sources are fertiliser, manure and untreated sewage (Bouwman et al., 2013). The planetary boundary focuses on major oceanic anoxic event, with impacts on marine ecosystems, and widespread eutrophication of freshwater systems. Although phosphorus impacts are usually considered regional rather than global issues, similar to the other biogeochemical flows (nitrogen) boundary, local and regional changes can cascade to global consequences by their relations with other planetary boundaries Furthermore, also for phosphorus, there are large differences between regions, with some having excess nutrient flows, while others are nutrient-deficient with negative impacts on agricultural productivity.

The original Rockström et al. (2009) paper focused on coastal systems only, proposing a control variable of inflow of phosphorus to the ocean. This indicator was retained in the updated paper of Steffen et al. (2015b), but based on Carpenter and Bennett (2011) they added phosphorus flow from fertilisers to erodible soils to also take into account freshwater eutrophication. It should be noted that this boundary is a global average, while regional distribution is critical for impacts. Furthermore, significant amounts of phosphorus are also applied as manure (Bouwman et al., 2017), but this is excluded as manure is in fact phosphorus recycled internally in the agricultural system. Steffen et al. (2015b) argue that it would be more appropriate to use the flow of phosphorus from soil to the freshwater system as the control variable, as this is more directly related to eutrophication, but this component is more difficult to measure than the application of phosphorus to soils and is also less amenable to management. Furthermore, they assume that all cropland soils are in principle 'erodible' in terms of flow of phosphorus from soil to fresh water. For the sake of data availability, especially with respect to footprint data, we focus on freshwater eutrophication, using the phosphorus fertilises use as the control variable.

Based on Carpenter and Bennett (2011), Steffen et al. (2015b) assume the riverine water quality criterion of 160 mg m^{-3} and a flow rate to the ocean of 9 Tg P yr^{-1}, concluding a planetary boundary of 6.2 Tg P yr^{-1}, with an uncertainty zone of 6.2–11.2 Tg P yr^{-1}, and a uniform application rate of phosphorus addition to cropland of 4.1–7.5 kg ha^{-1} yr^{-1}. Here, we use the same boundary values and uncertainty zone.

A.5 Biodiversity loss

The biosphere integrity boundary focuses on the vital role of the biosphere in Earth system functioning and thereby on biodiversity loss and extinctions. Its objective is to avoid a level of degradation that would lead to irreversible and widespread undesired states of ecosystems that significantly impact their provisioning of goods and services to society. It is the other core boundary that is strongly interlinked with the other boundary processes (Steffen et al., 2015b). Biodiversity loss is usually considered a regional issue, but it can cascade to the global level as its importance for ecosystem functioning and human well-being is considerable (Cardinale et al., 2012; Isbell et al., 2017). The biosphere integrity boundary is a strongly systemic boundary, interacting with and co-dependent on most other planetary boundaries (Mace et al., 2014). Land-system change, climate change, ocean acidification, and changes in nutrient and water cycles have large impacts on biodiversity and the biosphere in general. Biosphere changes including biome-level biodiversity loss in turn can affect climate, water and nutrient cycles.

Although it is now accepted that species richness underpins the resilience of ecosystems (Hooper et al., 2005; Isbell et al., 2017), little is known about how much and what kinds of biodiversity can be lost before this resilience is eroded (Rockström et al., 2009). Rockström et al. (2009) focused on anthropogenic biodiversity loss, proposing global species extinction rate as a control variable. However, the lack of well-established, universal, scalable or appropriate relationships and thresholds prevents this metric from effectively defining a safe operating space (Mace et al., 2014). In response, Mace et al. (2014) proposed three alternative metrics to base a boundary on: 1) a measure of phylogenetic diversity, representing the genetic library of life; 2) functional diversity; and 3) biome condition and extent. Based on this, Steffen et al. (2015b) reframed the 'biodiversity boundary' in terms of biosphere integrity, proposing two control variables: 1) genetic diversity; and 2) the role of the biosphere in Earth system functioning. For the first component, they retained the global extinction rate as an interim control variable. The second component focuses on the role of the biosphere in Earth system functioning, measuring loss of biodiversity components at global and biome/large ecosystem level, using the Biodiversity Intactness Index (BII). Both are interim control variables, to be used until more appropriate indicators are developed.

Here, we use the Mean Species Abundance (MSA) as control variable (Alkemade et al., 2009; Schipper et al., 2016). The MSA is defined as the mean abundance of original species in a disturbed situation relative to their mean abundance in an undisturbed reference situation. MSA is similar to the BII, except that MSA does not incorporate increases in abundance from undisturbed to disturbed conditions, i.e., if the abundance of a species is higher in the disturbed conditions as compared to the reference situation, the abundance of the reference situation is retained. As such, it is more of an 'early warning' indicator than BII, as abundance losses of a given species cannot be compensated for by increases in abundance of other species. Further, large-scale applications of the BII have been confined to land use and related impacts (Scholes and Biggs, 2005; Newbold et al., 2016), whereas response relationships for the MSA are available for multiple pressures, via the GLOBIO model (Alkemade et al., 2009; Schipper et al., 2016). GLOBIO has been used in various regional and global studies, including to assess future developments in global biodiversity loss (PBL, 2014; Van der Esch et al., 2017), to assess historic biodiversity loss in the EU and the Netherlands (PBL, 2012) and to quantify the biodiversity footprints of citizens and countries (Wilting et al., 2017).

Due to a lack of evidence on the relationship between BII and Earth system responses, Steffen et al. (2015b) propose a preliminary boundary of maintaining the BII at 90% or above, assessed geographically by biomes/large regional areas (e.g. southern Africa), major marine ecosystems (e.g. coral reefs) or by large functional groups, with a 90% to 30% uncertainty zone. In order to cope with the different metrics in the planetary boundary proposed by Steffen et al. (2015b) and our control variable, we used a simulation model to translate the BII-based boundary into a boundary in MSA terms. By using BII values per land-use type and land-use intensity data from Newbold et al. (2016), we simulated various combinations of land-use types with overall BII values of between 80% and 100%, and calculated the corresponding MSA values. The values for the MSA factors per land-use type were obtained from the GLOBIO model (Alkemade et al., 2009; Schipper et al., 2016). A regression analysis of the simulation outcomes resulted in a global planetary boundary of maintaining the MSA at 72% or above. This is the global limit we use. It was with the BII values from Newbold et al. (2016) not possible to simulate a situation with a BII at 30%. Therefore, we do not use an uncertainty zone for biosphere integrity.

Appendix B: Formula for allocation approaches

In our analysis we use six distinct allocation approaches, based on different underlying equity principles. The allocation approaches build on approaches applied in Van den Berg et al. (submitted). Here we present the derived equations for each of the approaches:

Grandfathering (GF):

$$pb_{c,r,GF} = \frac{e_{c,r,t=2010}}{E_{r,t=2010}} * PB_r$$

Per capita allocation (IEPC):

$$pb_{c,r,IEPC} = \frac{pop_{c,t}}{POP_t} * PB_r$$

Equal cumulative per capita allocation (ECPC):

$$pb_{c,r,ECPC} = \frac{\sum_{t=2010}^{t\_end} pop_{c,t}}{\sum_{t=2010}^{t\_end} POP_t} * PB_r$$

Ability to pay (AP):

$$pb_{c,r,AP} = e_{c,r,t=2010} - \left(\frac{e_{c,r,t=2010} \cdot \sqrt[3]{\frac{gdppc_{c,t}}{GDPPC_t}}}{\sum_c^{NC} e_{c,r,t=2010} \cdot \sqrt[3]{\frac{gdppc_{c,t}}{GDPPC_t}}} \cdot (E_{r,t=2010} - PB_r) \right)$$

Development Rights (DR):

$$pb_{c,r,DR} = e_{c,r,t=2010} - \left(\frac{rci_{c,t=2010}}{RCI_{t=2010}} \cdot (E_{r,t=2010} - PB_r) \right)$$

Resource efficiency (RE):

$$pb_{c,r,RE} = e_{c,r,t=2010} - \left(\frac{e_{c,r,t=2010} \cdot \frac{re_{c,t=2010}}{RE_{t=2010}}}{\sum_c^{NC} e_{c,r,t=2010} \cdot \frac{re_{c,t=2010}}{RE_{t=2010}}} \cdot (E_{r,t=2010} - PB_r) \right)$$

pb = scaled planetary boundary; PB = planetary boundary level; e = country-level environmental pressure; E = global environmental pressure; pop = country-level population; POP = global population; gdp_{pc} = country-level per capita GDP; GDP_{pc} = global per capita GDP; rci = country-level responsibility capability index; RCI = responsibility capability index summed over all countries; re = country-level resource efficiency; RE = global resource efficiency; c = country; r = planetary boundary, t = year

Appendix C: Methodology for footprint calculations

In this study, we compared the translated planetary boundaries against production- and consumption-based indicators at the national level, which were used as a benchmark (in Chapter 4). These indicators were calculated at three spatial levels: the Netherlands, the European Union[7], and the whole world.

The production-based indicators are straightforward and were purely based on environmental accounts and statistics. We used a multi-regional input-output (MRIO) model in order to calculate the consumption-based (footprint) indicators. Such an MRIO model relates production and environmental pressures in one region via international trade flows to consumption in other regions. At the global level, total environmental pressures and impacts are the same from a production-based and a consumption-based perspective, but due to trade flows they differ at regional levels. The MRIO model used consists of 41 regions and 39 sectors (Tables A1, A2). Environmental footprints were calculated for the year 2010, which was the base year of the benchmark. In order to identify trends in the indicators we investigated the 1995–2010 period, as well. Figures per capita were calculated with data on population per country obtained from UN (2017b).

C.1 Environmental footprint model

The calculation of the environmental footprints related to Dutch and EU consumption was carried out by using MRIO analysis. The general MRIO model for calculating the environmental footprint, depicting the environmental pressures related to final demand, E_i, in a certain country or region i, is:

$$E_i = d\,(I - A)^{-1}\,y_i + D_i \qquad (1)$$

with

- d — row vector of direct environmental pressure intensities (depicting the pressure from one unit of production for all sectors and regions).
- A — matrix of input coefficients covering all regions and sectors in the model; this matrix is based on domestic economic input-output tables per region and trade flows between regions. The domestic and import coefficients depict the intermediate input requirements per unit of production (output) for each sector.
- I — identity matrix with 'ones' at the diagonal of the matrix and 'zeros' for all other elements of the matrix; matrix $(I - A)^{-1}$ is the Leontief inverse matrix, named after the founding father of IO analysis, Wassilli Leontief (Dietzenbacher and Lahr, 2004).
- y_i — vector of final demand of region i; this vector includes both domestically produced final demand as well as final demand imported from other regions. Final demand concerns demand for final goods and services, including investments and private and public consumption.
- D_i — scalar: direct environmental pressure of final demand in region i.

The model for calculating biodiversity footprints is an extension of the environmental footprint model by including biodiversity impact factors. These impact factors depict the biodiversity impact per unit of environmental pressure. The formula for calculating the biodiversity footprint, depicting the biodiversity impact related to final demand, B_i, in a certain country or region j, is:

$$B_j = i\,(M \circ D)\,(I - A)^{-1}\,y_j + m_j\,d_j \qquad (2)$$

with

- i — vector of ones required to sum the biodiversity losses of individual environmental pressures;
- M — matrix of biodiversity impact factors depicting the biodiversity impacts per unit of environmental pressure;

[7] The EU includes here the 27 countries that were member in 2010, so excluding Croatia.

D matrix of direct environmental pressures depicting the direct environmental pressures of one unit of production for all sectors;
I identity matrix;
A matrix of input coefficients;
y_j vector of final demand of region j;
m_j vector of biodiversity impact factors related to direct environmental pressures of final demand in region j;
d_j vector of the direct environmental pressures from final demand in region j.

Operation $\circ$ is the element-wise multiplication of two matrices. The input-output formalism also enables the calculation of a breakdown of the national footprints into regions and sectors of origin as well as the breakdown into consumption categories. More comprehensive descriptions are available in the input-output literature (e.g. Miller and Blair, 2009).

C.2 Overview of the data sources

The MRIO model requires economic input-output data and environmental data from several sources. In this study, we considered CO_2 emissions, land use, nitrogen and phosphorus, and biodiversity loss (see also Appendix A). To calculate biodiversity impacts also CH_4 and NO_2 emissions are used.

C.2.1 Economic data

Building on previous work (Wilting, 2014), we obtained input-output data from the World Input-Output Database (WIOD), which describes the global economy, over the 1995–2011 period (Timmer et al., 2015). The database contains input-output data at the level of 35 sectors in 40 countries and a region called Rest of the world (RoW). We downloaded MRIO tables for the 1995–2010 period from the WIOD website (www.wiod.org; World Input-Output Tables, Release 2013). Final demand categories, including household consumption, government consumption and investments, were aggregated to one final demand vector per region.

WIOD consists of one aggregated agricultural sector. This is a relevant issue in compiling some of the environmental footprints, such as carbon and land footprints. Agriculture has a large contribution in non-CO_2 greenhouse gas emissions and land use, but the shares of agricultural sub-sectors, such as arable farming and livestock farming, in these pressures differ significantly. For instance, pigs and chicken are more often than bovine cattle, sheep and goats kept in stables with relatively low land use per animal. We used data from EXIOBASE version 3 (Stadler et al., 2018) to further disaggregate the agricultural sector in WIOD.

We disaggregated the WIOD agricultural sector in the following five sub-sectors: crops, livestock with land, livestock without land, forestry and fisheries. In preparation of the disaggregation, the MRIO tables from EXIOBASE for the 1995–2010 period were aggregated to two levels; (i) the original WIOD classification with one agricultural sector; (ii) the WIOD classification extended with the detailed agricultural sub-sectors. On the basis of these two EXIOBASE-based tables, we derived shares presenting the shares of agricultural sub-sectors in total agriculture. These shares concern cells in the intermediate matrix, the final demand matrix and total production. All these shares were used to disaggregate the rows and columns corresponding to agriculture in the WIOD MRIO tables by maintaining the WIOD totals. In disaggregating the intermediate matrices, first the cells in rows were disaggregated and after that the cells in columns. The application of the procedures mentioned resulted in a WIOD-based MRIO table of 41 regions and 39 sectors per region. Final demand still consisted of one vector per region. After applying this procedure for disaggregating the agricultural sector, the column and row totals of the agricultural sub-sectors in the final table were not balanced anymore. Therefore, we applied a RAS procedure to rebalance these tables, keeping the new table consistent with the original WIOD table (Stone, 1961; Miller and Blair, 2009).

C.2.2 Greenhouse gas emission data

The planetary boundary for climate change is based on CO_2 emissions (See Appendix A.1). In order to calculate corresponding footprints we required data on CO_2 emissions in line with the WIOD MRIO tables. The calculation of the biodiversity footprints require data on emissions from CH_4 and N_2O as well. Data on greenhouse gas emissions for the 41 WIOD regions for the years 1995 through 2009 were derived from WIOD (emissions to air by sector and pollutant). We adjusted the greenhouse gas emission data for these years at one point. In WIOD, methane emissions related to landfills are allocated to the government sector (WIOD sector 34). Usually in environmental accounts (NAMEAs) these emissions are not allocated to industrial sectors or households, but are reported separately. Therefore, we moved the main part (99%) of the methane emissions allocated to the government sector to direct emissions of final demand in all regions. Furthermore, we estimated greenhouse gas emission data for 2010 by calculating a trend in emission intensities per sector and region and applying the 2010 intensities to production figures from WIOD. These data adjustments are in line with the calculations in Wilting (2014).

Since WIOD does not provide greenhouse gas emission data for the agricultural sub-sectors, we obtained such data from EXIOBASE. We calculated shares of greenhouse gas emissions in the five agricultural sub-sectors from the EXIOBASE data and applied these shares to the WIOD greenhouse gas emissions for agriculture. This is a similar approach as the disaggregation of total production in agriculture as done in the MRIO table.

We expressed all greenhouse gas emissions in CO_2 equivalents by using Global Warming Potentials (GWPs) taken from (Myhre et al., 2013). The GWPs used for presenting CH_4 and N_2O in terms of CO_2 equivalents are 28 and 265, respectively. These figures are for a time horizon of 100 years, consistent with those by IPCC (2013).

C.2.3 Land-use data

The planetary boundary for land-system change is based on the use of crop land. However, in order to calculate biodiversity footprints, we also required data on the size of areas for pasture, forestry, infrastructure and built-up land per country. Furthermore, for determining the impacts of infrastructure on biodiversity we also required data on the lengths of roads.

We obtained data on land use in the five agricultural sub-sectors from FAOStat (FAO, 2017). The data for more than 220 regions were aggregated to the 41 regions in our analysis. We assigned the total areas per region on *temporary crops*, *permanent crops* and *fallow land* to the crop sector (sector 1) in our model. In case of missing data (for *temporary crops* or *fallow land*) we calculated total crop land as *arable land + permanent crops—temporary meadows and pastures*.

Land use for pasture was directly obtained from FAOStat (*Permanent meadows and pastures*, and *temporary meadows and pastures*) and assigned to the sector livestock with land. The data set for *temporary meadows and pastures* showed several years with missing data. In that case we choose the figure from the closest year for which data were available. We just included intensively used pasture areas in the figures by adjusting the FAO data with figures on the shares of intensive and extensive used pasture from the IMAGE model (Stehfest et al., 2014).

Land use for forestry products in 2010 was based on figures from the global terrestrial biodiversity model GLOBIO (Alkemade et al., 2009) (areas for *Tree cover, plantation and managed*). Data for other years were derived by using data on removals of wood products (*Production of industrial roundwood*) from FAOStat. For each year, the ratio between the wood production for the specific year and wood production in 2010 was multiplied with the forestry area in 2010. The underlying assumption was that the volume of wood produced per hectare, per region, did not change over the 1995–2010 period.

We obtained data on road areas and lengths from the Global Roads Inventory Project (Meijer et al., 2018) and on the built-up areas (artificial surfaces) from the GLOBIO model (Alkemade et al., 2009). Data on built-up land and roads were only available for the year 2010.

C.2.4 Nitrogen data

We based the nitrogen footprint on the combination of phosphorus fertiliser use (cropland and pasture) and intentional phosphorus fixation by crops only. The data for phosphorus fertiliser use and phosphorus fixation were obtained from the IMAGE-Global Nutrient Model (GNM) as described in Bouwman et al. (2017). These data were aggregated to the WIOD countries and assigned to the crop and grass sectors (sectors 1 and 2) in the MRIO model.

The data for phosphorus fertiliser use were consistent with the data reported by FAOStat. For phosphorus fixation we used the figures given for crops. The crop areas in the IMAGE-GNM were different from the areas reported by FAO (and used in our MRIO model). To be consistent with the cropland areas that we used in the cropland footprint calculations, we derived N fixation intensities (kg N/ha) from the IMAGE-GNM and applied them to the crop areas that we used in our model.

C.2.5 Phosphorus data

We based the phosphorus footprint on the use of phosphate (P_2O_5) fertiliser. We obtained data on P_2O_5 fertiliser application per country, over the 1995–2010 period, from the IMAGE-Global Nutrient Model (Bouwman et al., 2017). In general, P_2O_5 fertiliser is applied on cropland, but in some countries, it is also applied on grassland. We assigned the data on P_2O_5 fertiliser use to cropland and grassland in the corresponding sectors, in the MRIO model.[8] Finally, all figures were expressed as phosphorus by multiplying the phosphate figures with a factor that was based on the molecular weights of phosphorus and phosphate (approximately 62/142).

C.2.6 Biodiversity impact data

The biodiversity footprint for the base year of 2010 was calculated as described in Wilting et al. (2017). The footprint includes impacts on biodiversity due to habitats being replaced with cropland, pasture, forest and built-up area; land fragmentation by cropland and infrastructure; and disturbance by infrastructure, encroachment and climate change (greenhouse gas emissions). The translation of environmental pressures into biodiversity loss was based on biodiversity loss factors obtained from the GLOBIO model (version 3.5). GLOBIO calculates remaining biodiversity, expressed as the mean species abundance (MSA) of originally occurring species, in relation to various environmental pressures including climate change, land use and infrastructure.

The model has a spatial resolution of 0.5° by 0.5°. To obtain land-related biodiversity loss factors (in MSA loss per ha, per unit of land use or roads), we first aggregated the pressure-specific MSA losses, as calculated with the GLOBIO model, either per MRIO region (for land use and infrastructural pressures). Then, the aggregated loss in MSA due to a particular pressure was divided by the cumulative amount of that pressure, to arrive at the MSA loss per ha of annual land use or km of road. Biodiversity loss factors for habitat replacement by cropland, pasture, forestry, and built-up area were retrieved from the MSA values and areas of these land-use types per region. Biodiversity loss factors for disturbance and fragmentation of natural habitat by roads were obtained from the respective MSA values combined with the road length per region, in order to determine the loss per kilometre of road length.

Biodiversity loss factors of greenhouse gas emissions (in MSA loss per ha, per year, per kg CO_2 equivalents) were based on the time-integrated global temperature potential of greenhouse gases (Joos et al., 2013) and the relationship between an increase in global mean temperature and losses in MSA per biome (Arets et al., 2014). On the basis of these relationships, we derived one average value for MSA loss caused by global greenhouse gas emissions considering a time horizon of 100 years, consistent with IPCC (IPCC, 2013). More details on the calculation of the loss factors are provided in the Supplementary Info in Wilting et al. (2017).

We calculated the biodiversity footprint as discussed just for 2010. Since data on built-up areas and roads were not available for the whole 1995–2010 period, we calculated a consistent biodiversity footprint time series for these years on the basis of the use of cropland, pasture land and forestry land, and greenhouse gas emissions. So, for the year 2010 we calculated two biodiversity footprints; (i) a complete one including impacts of infrastructure, and indirect impacts of land use, and (ii) a footprint including the biodiversity impacts of greenhouse gas emissions and direct habitat only.

C.3 Consumption categories

The environmental footprint of a region depicts the overall environmental pressures related to total final consumption in a that region. We calculated footprints for five specific

[8] The control variable of Steffen et al. (2015b) is only for cropland. However as the pasture share is relatively small (2-3% of total for both nitrogen and phosphorus), we did not separate the two in order to receive complete footprints.

consumption categories, viz. food, transport, housing, goods and services, by mapping these categories to the economic sectors in the MRIO model (Table A3). The results are indicative, since most economic sectors do not completely match with one consumption category. Furthermore, direct environmental pressures from consumers were mapped to consumption categories too (Table A2).

Table A1
Countries and regions in the MRIO footprint model.

1	Australia		**22**	Italy	EU
2	Austria	EU	**23**	Japan	
3	Belgium	EU	**24**	South Korea	
4	Bulgaria	EU	**25**	Lithuania	EU
5	Brazil		**26**	Luxembourg	EU
6	Canada		**27**	Latvia	EU
7	China		**28**	Mexico	
8	Cyprus	EU	**29**	Malta	EU
9	Czech Republic	EU	**30**	Netherlands	EU
10	Germany	EU	**31**	Poland	EU
11	Denmark	EU	**32**	Portugal	EU
12	Spain	EU	**33**	Romania	EU
13	Estonia	EU	**34**	Russia	
14	Finland	EU	**35**	Slovak Republic	EU
15	France	EU	**36**	Slovenia	EU
16	United Kingdom	EU	**37**	Sweden	EU
17	Greece	EU	**38**	Turkey	
18	Hungary	EU	**39**	Taiwan	
19	Indonesia		**40**	United States	
20	India		**41**	Rest of the World	
21	Ireland	EU			

Table A2
Allocation of direct environmental pressures by consumers to six main consumption categories.

	Housing	Transport	Food	Goods	Services	Not allocated
CO_2[1]	x	x				
CH_4						x
N_2O		x				
Crop land			x			
Pasture land			x			
Forest land	x					
Roads		x				
Urban area						x

[1] Allocation to consumption categories by using CO_2 emissions per energy carrier (e.g. natural gas, motor fuel) from the WIOD database.

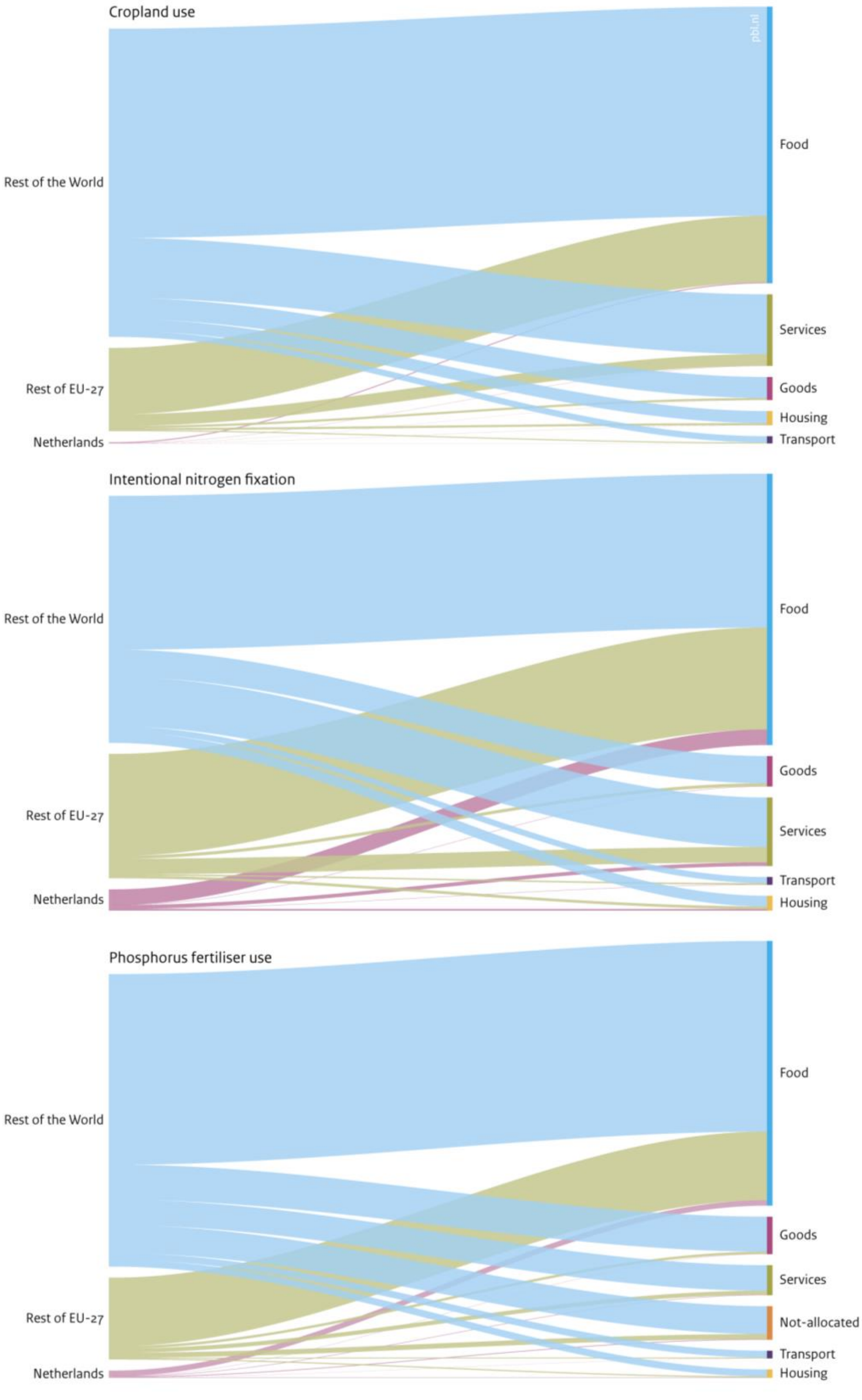
Table A3
Coupling between MRIO sectors and six main consumption categories.

	MRIO sector	Housing	Transport	Food	Goods	Services
1	Crops			x		

2	Livestock, land related			x		
3	Livestock, not land related			x		
4	Forestry				x	
5	Fishing			x		
6	Mining and Quarrying	x				
7	Food, Beverages and Tobacco			x		
8	Textiles and Textile Products				x	
9	Leather, Leather and Footwear				x	
10	Wood and Products of Wood and Cork				x	
11	Pulp, Paper, Paper, Printing and Publishing				x	
12	Coke, Refined Petroleum and Nuclear Fuel		x			
13	Chemicals and Chemical Products				x	
14	Rubber and Plastics				x	
15	Other Non-Metallic Mineral				x	
16	Basic Metals and Fabricated Metal				x	
17	Machinery, not else classified				x	
18	Electrical and Optical Equipment				x	
19	Transport Equipment		x			
20	Manufacturing, not else classified; Recycling				x	
21	Electricity, Gas and Water Supply	x				
22	Construction	x				
23	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel		x			
24	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles					x
25	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods					x
26	Hotels and Restaurants					x
27	Inland Transport		x			
28	Water Transport		x			
29	Air Transport		x			
30	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies		x			
31	Post and Telecommunications					x
32	Financial Intermediation					x
33	Real Estate Activities	x				
34	Renting of Machinery and Equipment, and Other Business Activities					x
35	Public Administration and Defence; Compulsory Social Security					x
36	Education					x
37	Health and Social Work					x
38	Other Community, Social and Personal Services					x
39	Private Households with Employed Persons					x

Appendix D: Breakdown of environmental footprints

Figure D1
Share of consumption categories (right) linked to origin of production (left), 2010



Source: PBL