EEA Report | No 01/2020

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An assessment of Europe's environmental footprints in relation to planetary boundaries

Joint EEA/FOEN Report

ISSN 1977-8449

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Cover design: EEA
Cover photo: © Ben Heslop, Picture2050/EEA
Layout: Rosendahls a/s

Luxembourg: Publications Office of the European Union, 2020

ISBN 978-92-9482-215-6
ISSN 1977-8449
doi:10.2800/890673

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Acknowledgements

This report is the result of a collaboration between the Swiss Federal Office for the Environment (FOEN) and the European Environment Agency (EEA). FOEN and the EEA provided funding for the work on this report.

The report was authored by Frank Wugt Larsen and Tobias Lung from the EEA with contributions from Andreas Hauser from FOEN. It received strategic direction from a steering committee consisting of the authors and Jock Martin (EEA) and Nicolas Perritaz (FOEN).

The report builds upon an internal analysis and report provided to the EEA and FOEN by Damien Friot (Shaping Environmental Action) and Hy Dao (United Nations Environment Programme (UNEP) Global Resource Information Database (GRID-Geneva), supported by Rolf Frischknecht (treeze), Eva Gladeck (Metabolic) and Cassie Bjorck (Metabolic).

We are grateful for feedback on draft versions given by Cathy Maguire (EEA) and institutional partners from the Environmental Knowledge Community (EKC). We also gratefully acknowledge support from Andreas Bachmann (FOEN) and Niklas Nierhoff (FOEN).

Foreword

The diagnosis is clear. Planet Earth faces pressures from human development that are unprecedented in scale and urgency. The planetary boundaries framework confronts us with limits to the amount of such pressures, beyond which we risk potentially irreversible consequences for human development. Critically in this context, and to quote former UN Secretary-General Ban-Ki Moon, echoed by young people around the world, we do not have a 'planet B'.

This study considers the planetary boundaries framework at the European level and shows that Europe is indeed exceeding its limits. Interestingly, the largest shares of many countries' environmental footprints occur abroad. This is particularly the case for small open economies such as Switzerland. Taking such indirect environmental pressures into account is an indispensable complement to traditional domestic-oriented policies.

These findings call for urgent action beyond the steps currently being taken. Achieving the Sustainable Development Goals will be impossible without respecting planetary boundaries. It is up to national and European bodies to incorporate the realities of planetary limits into their work. The EEA and Switzerland have been instrumental in operationalising the planetary boundaries concept in this context.

Overall, it is clear that current policies are not sufficient. The new European Green Deal announced lately by the European Commission is opportunity for Europe to radically shift course. We need an economy that works for our planet and delivers prosperity and well-being at the same time. Such initiatives have to be accompanied by public dialogue on how we want to shape the future within planetary limits.

This will require re-thinking of our individual habits and lifestyles, but also fundamental changes to key systems of production and consumption. Food and agriculture — identified as key in relation to several large-scale Earth system pressures – is one system for which European policies need to be radically different from those of the past decades. International research, such as the 2019 EAT-Lancet report, demonstrates that there are clear dietary and ecological benefits from a better, more balanced diet.

The business sector, along with governments and scientists, can play a crucial role by developing and exporting innovative, future-fit products and services. Novel solutions are urgently needed in areas such as food and agriculture, and construction and housing, as well as mobility. Companies are making increasing use of tools based on life cycle assessment when analysing the extent to which their business model is future fit.

It is time for us all to drive innovation with the goals of developing the technological alternatives and mindsets to catalyse the transformation of consumption and production patterns. Governments have to create the framework conditions and incentives needed and lead by example, e.g. through green public procurement.

Time is running out, but it is not too late to avoid irreversible impacts from climate change, biodiversity loss and over-consumption of resources. Europe can make the difference. Let's take bold action towards a future that brings Europe back into a 'safe operating space'.

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Executive Director
European Environment Agency, Copenhagen

Christine Hofmann
Director a.i.
Federal Office for the Environment, Bern

Preface

This report has its roots in the Environmental Knowledge Community (EKC). The EKC was founded in early 2015 as a collaboration of six European Union institutions — the European Commission Directorate-General (DG) for the Environment, DG Climate Action and DG Research and Innovation, as well as Eurostat, the Joint Research Centre (JRC) and the European Environment Agency (EEA). In 2018, DG Agriculture and Rural Development also joined. The EKC's aim is to exploit new ways of collaboration and knowledge co-creation geared towards supporting future policy developments.

The successful delivery and maintenance of European policies on the environment and climate requires working beyond traditional silos. Policymaking will increasingly rely on understanding the complex interactions occurring between the various environmental media. Therefore, the EKC has initiated a number of cross-cutting knowledge innovation projects (KIPs), one of which is on planetary boundaries ('within the limits of our planet' — WiLoP). As a response to knowledge needs for policymaking in combination with significant recent scientific advances in the field of Earth system sciences, the work aims to help operationalise the planetary boundary concept in an EU policy context.

In this regard, the EEA, during the first phase of the WiLoP project (2016-2017), discussed possible approaches to the project's implementation given its relative novelty, and partnered with the Stockholm Environment Institute (SEI), the Stockholm Resilience Centre (SRC) and the Netherlands Environment Assessment Agency (PBL) to establish the project's scope and possible analytical pathways.

The second phase of the WiLoP project (2018-2019) has focused, in collaboration with the Swiss Federal Office for the Environment (FOEN) on advancing the analysis of planetary boundaries on the European scale. Switzerland is a frontrunner country with respect to approaches to operationalising the planetary boundaries concept on a national scale. The Swiss government assessed, among other things, planetary boundaries in its 2018 state of the environment report and anchored them in the Swiss sustainable development strategy 2016-2019. Switzerland also regularly monitors its environmental footprints against planetary boundaries.

This report represents the fruits of that cooperation and should be seen as a basis for furthering discussions on how to operationalise the planetary boundaries framework for EU policies. The European Green Deal provides a new framework for those considerations and, with its focus on systemic challenges and sustainability, arguably provides a more relevant basis for WiLoP-type analysis than before.

Executive summary

Introduction and objectives

Human development patterns and economic activities have resulted in sustainability challenges of unprecedented scale and urgency, e.g. in terms of climate change and global biodiversity loss. This worrying development gives rise to the critical question of whether or not human-induced pressures now approach or exceed planet Earth's environmental limits. Are current pressures on the Earth system in terms of, for example, levels of greenhouse gas (GHG) emissions, ecosystem degradation or global resource use jeopardising the stability of the Earth system?

The planetary boundaries framework identified nine processes that regulate the stability and resilience of the Earth system — 'Earth life-support systems'. The framework proposes precautionary quantitative planetary boundaries within which humanity can continue to develop and thrive, referred to as a 'safe operating space'. It suggests that crossing these boundaries increases the risk of generating large-scale abrupt or irreversible environmental changes that could turn the Earth system into a state that is detrimental for human development. The most recent estimate suggests that four Earth system processes — climate change, biosphere integrity, land system change and biogeochemical cycles — are in a zone of increasing risk of triggering fundamental and undesirable Earth system changes.

The EU has responded to these challenges by committing to a range of long-term sustainability goals with the overall aim of 'living well, within the limits of our planet'. A similar objective is embedded in Switzerland's 2016-2019 sustainable development strategy. The European Commission for the period 2019-2024 raised ambitions further by setting out an agenda for a European Green Deal, stating that, 'Europe must lead the transition to a healthy planet'. Nonetheless, it is not clear what it means for Europe to live 'within the limits of our planet'. What is the environmentally safe operating space for Europe and how can whether Europe is living within it be determined in practice?

This report builds on past work by the European Environment Agency (EEA) on operationalising the planetary boundaries framework in Europe and the experiences of the Swiss Federal Office for the Environment (FOEN) in measuring its environmental footprints against planetary boundaries. Overall, this report aims to explore ways of defining an environmentally safe operating space for Europe and to test the approach on a number of selected planetary boundaries. This involves two specific steps that build upon each other:

1. The first step explores how to define European shares of the global safe operating space. Such a definition of shares inevitably involves normative choices. Most previous scientific studies have employed the equality principle only, which assumes the basic idea of equal rights for all humans on Earth. This report takes an important step forward by exploring multiple allocation principles to define shares depending on normative choices regarding aspects such as human needs, right to development, sovereignty and capability, independently of any specific planetary boundary. The resulting shares are subsequently used to calculate actual European limits for three selected planetary boundaries.

2. The second step is to evaluate the extent to which current European environmental footprints are compatible with the European limits as calculated for the three planetary boundaries in step 1. The report calculates European footprints based on a state-of-the-art multiregional input-output (MRIO) model and compares them with the calculated European limits to assess whether or not Europe is living within its environmentally safe operating space.

The analysis covers the combined territory of the 33 member countries of the EEA (the 28 EU Member States plus Iceland, Liechtenstein, Norway, Switzerland and Turkey). The report addresses three planetary boundaries in a European-scale analysis: phosphorus and nitrogen cycles (these biogeochemical flows are

addressed as two separate Earth system processes in this report), land system change and freshwater use. In addition, a case study for Switzerland on biosphere integrity (genetic diversity) is included.

Defining European shares of the global safe operating space to determine a European safe operating space

Applying the globally defined planetary boundaries framework to Europe requires a definition of Europe's shares of the global safe operating space. Such scale matching of planetary boundaries inevitably involves normative choices regarding aspects of fairness, equity, international burden sharing and the right for economic development. The experience of the United Nations Framework Convention on Climate Change (UNFCCC) negotiations regarding climate change offers insights into different options for implementing the notions of equity and fairness. The report explores five different allocation principles (see Table ES.1), with multiple calculations being used to derive values based on each principle, to effectively represent a range of different ways of implementing these normative choices.

The application of these five allocation principles, by performing a total of 27 different calculations, results in an overall median European share of 7.3 % of the global limit, independently of any specific planetary boundary. The allocation principle of 'right to development' results in the lowest median European share (4.1 %), while 'sovereignty' results in the highest (12.5 %).

European performance: are Europe's environmental footprints within European limits?

This report's calculation of European performance takes a consumption-based perspective (also referred to as environmental footprint perspective), which relates environmental pressures to final demand for goods and services. It takes into account today's globalised economy with trade flows between regions and countries and therefore also accounts for the environmental pressures caused around the world by European domestic consumption. The footprints have been calculated based on a state-of-the-art MRIO model — Exiobase (http://www.exiobase.eu) — which was developed through a Seventh Framework Programme (FP7) research project (Desire) funded by the European Commission.

A comparison of European footprints with European limits for the selected planetary boundaries shows that the European footprints exceed the European limits for three out of four Earth system processes, namely for the nitrogen cycle (expressed as nitrogen losses in this report) and the phosphorus cycle (expressed as

Table ES.1 Overview of allocation principles applied in this study

Allocation principle ([a])	Description	Median European share
Equality (9)	People have equal rights to use resources, resulting in an equal share per capita. Equality can be envisaged between people living in a particular year or between people over time.	8.1 %
Needs (4)	People have different resources needs. This could be due to their age, the size of the household they live in or their location. As a result, their right to resources could be differentiated.	7.3 %
Right to development (3)	People have the right to have a decent life (e.g. rights for covering basic needs). In the long term, a convergence of welfare between people could be envisaged. People in countries with lower development levels could thus be allocated more resources to meet development objectives.	4.1 %
Sovereignty (5)	Apart from international treaties and regional arrangements (e.g. the European Union), countries are managed based on national policies and have a legal right to use their own territory as they decide. This implies that levels of economic throughput and environmental impacts (generated domestically and in foreign economies) are taken as starting points for allocating the global budget on national scales.	12.5 %
Capability (6)	Countries have different levels of economic wealth. Countries with higher financial capabilities could contribute proportionally more to the mitigation efforts or use less than their allocated share of resource since their ability to pay is higher.	6.2 %

Note: ([a]) Number of calculations in brackets.

phosphorus losses) — that is, for both biogeochemical flows considered — and for land system change (expressed as land cover anthropisation) (Figure ES.1).

Any analysis of this type to assess whether Europe lives 'within the limits of our planet' is subject to some inherent methodological uncertainties, in particular in relation to estimating global limits, defining European shares and computing European footprints. Nevertheless, the results of this report are based on a consistent footprint methodology (through the use of Exiobase 3.4) and support the findings of two previous Europe-wide studies. Both studies concluded that Europe exceeds its limits for the nitrogen, phosphorus and land systems boundaries and did not overshoot the freshwater boundary. Thus, the results related to overall European performance presented in this report are considered fairly robust.

Specific key findings

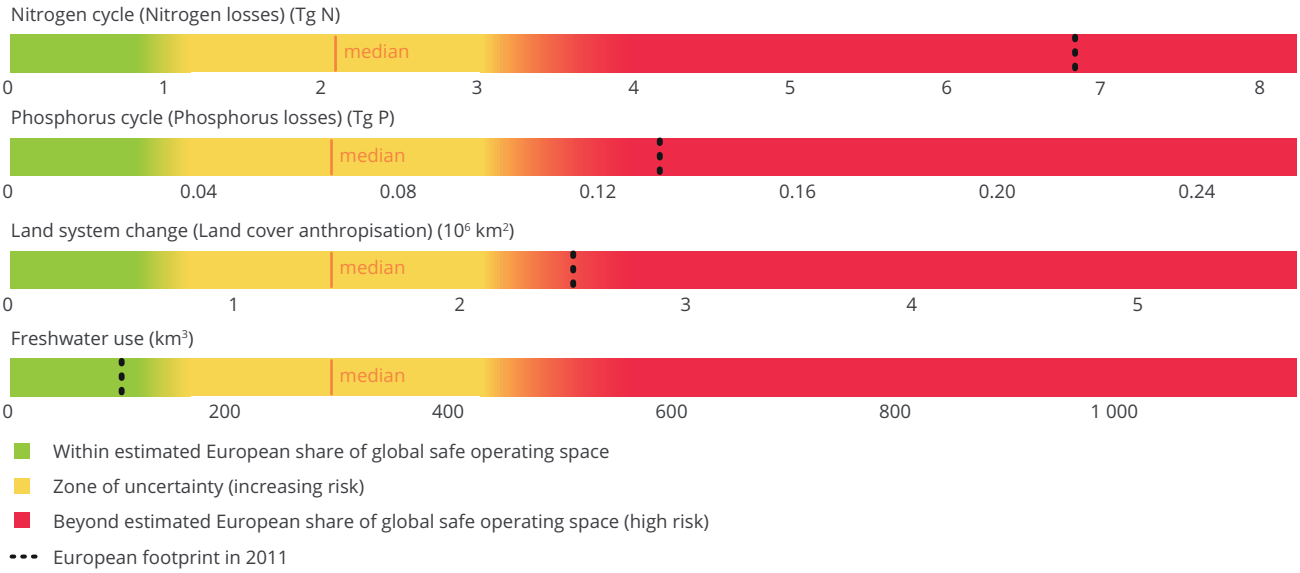
Nitrogen cycle (biogeochemical flows): the calculated European limit for nitrogen losses is exceeded for all allocation principles. Using the median value across all allocation principles, the European limit for nitrogen losses is exceeded by a factor of 3.3. In comparison, the global limit for nitrogen losses is exceeded by a factor of 1.7.

Phosphorus cycle (biogeochemical flows): the calculated European limit for phosphorus losses is exceeded for all allocation principles except 'sovereignty'. Using the median value across all allocation principles, the European limit for phosphorus losses is exceeded by a factor of 2. In comparison, the global limit for phosphorus losses is also exceeded by a factor of 2.

Land system change: the calculated European limit for land cover anthropisation is exceeded for all allocation principles except 'sovereignty'. Using the median value across all allocation principles, the European limit for land cover anthropisation is exceeded by a factor of 1.8. In comparison, the global limit for land cover anthropisation is not exceeded.

Freshwater use: the European limit for freshwater use is not exceeded for any allocation principle. Using the median value across all allocation principles, the European freshwater footprint is below the European limit by a factor of 3. In comparison, the global freshwater footprint is below the global limit by a factor of 3.3. However, this does not preclude the potential local overconsumption of freshwater at the basin level and issues with water scarcity in southern Europe.

Figure ES.1 Overview of European performance for three planetary boundaries



Note: The yellow range of the figure represents the average range across the five allocation principles, with a median of 7.3 %. This yellow range is defined as the 'zone of uncertainty' to reflect the normative process of defining a European 'safe operating space'.

Source: Own calculations.

Case study on biodiversity for Switzerland

An explorative assessment of Switzerland's biodiversity footprint against planetary boundaries is included. The footprint was calculated by considering the potential for global species loss because of land use. An equal share per capita approach was used to calculate the Swiss share of the biosphere integrity planetary boundary. The Swiss biodiversity footprint exceeds the resulting threshold value by a factor of 3.7. The indicators applied inevitably simplified the complex issue of biosphere integrity.

Implications for policy and knowledge developments

Substantial policy focus on different scales of governance has been dedicated to the challenge of climate change, and increasingly also to global biodiversity loss. These are also high priorities in political guidelines (European Green Deal) for the European Commission in the period 2019-2024. Climate change and biodiversity loss are crucial systemic issues in themselves, but they are also intimately linked to other Earth system processes. In the planetary boundaries framework, climate change and biosphere integrity are the two core boundaries given that they are highly important for the Earth system and their systemic interactions with other Earth system processes (e.g. land system change and biogeochemical cycles). Therefore, progress towards addressing the issues of climate change and biodiversity loss could be hampered by a lack of progress towards addressing the exceedances of other planetary boundaries such as biogeochemical cycles, land system change and freshwater use.

The findings of this report highlight that Europe should prioritise these additional key systemic challenges, in particular the nitrogen and phosphorus cycles and land system change. The findings of this report suggest that the European footprint should be reduced by about a factor of 3 for nitrogen losses and a factor of 2 for phosphorus losses. In addition, a reduction by almost a factor of 2 is needed for land cover anthropisation. Currently, the systemic challenges related to the nutrient cycle (nitrogen and phosphorus cycles) and land system change are not being sufficiently addressed by policy in an integrated and systemic way. The development and implementation of an Eighth Environment Action Programme (8th EAP) under the European Green Deal provides an opportunity to better operationalise the meaning of 'living well, within the limits of our planet' by capturing more comprehensively the systemic nature of the nutrient and land system challenges, their interlinkages and the need to address them in a holistic manner. It also provides an opportunity to address the environmental pressures that Europe exerts abroad.

It is increasingly acknowledged that profound transformations of the current systems of consumption and production will be needed to address the underlying drivers of unsustainability. These systems, such as food, energy and mobility, are ultimately the root causes of the exceedance of many planetary boundaries. The specific boundaries assessed in this study — the nitrogen cycle, the phosphorus cycle, land system change and freshwater use — are particularly driven by the food system.

Thus, a key leverage point is to transform the food system. Embracing a wider food system perspective — beyond thematic and sectoral policies — would be particularly beneficial, because diffuse nutrient pollution is also influenced by society's consumption patterns, such as in terms of food choices and food waste. There are already growing calls for the EU to develop a 'common food policy'. The European Green Deal envisages a 'farm to fork strategy' on sustainable food along the whole value chain, which provides exactly such an opportunity to build a comprehensive policy framework addressing these root causes.

This report supports the growing scientific evidence that the resource use related to current European production and consumption patterns puts Earth's life-support systems at risk and with it society and the foundation for economic development. From a technical point of view, the report provides some important advances in understanding how the concept of planetary boundaries can be operationalised in Europe and also sheds light on knowledge gaps. Examples of such advances are (1) a better understanding of global environmental limits (i.e. some boundaries lack limits and some control variables are only interim), (2) a better understanding of the interdependencies and feedback loops between globally and regionally determined boundaries, and (3) a better understanding of European environmental footprints and the spatial patterns of negative environmental impacts from European consumption in other parts of the world.

1 Introduction

1.1 Global environmental limits and the planetary boundaries framework

Most achievements of humanity — farming, cities, culture, industrialisation and medical advances — have happened during a period in which Earth's natural regulatory systems, such as the climate, the soil or freshwater supply, have been relatively stable. These stable conditions are referred to as the Holocene. While rapid human development over the past 150 years has enhanced well-being for many, it has also put tremendous pressures on Earth's life-support systems and natural resources. Scientists refer to this new human-dominated era as the Anthropocene (Waters et al., 2016; Steffen et al., 2018).

The ever increasing demands of 7.7 billion people — which may rise to 9.7 billion by 2050 (UN DESA, 2019) — give rise to questions about whether and at what point human pressures will exceed the tolerance levels of Earth's life-support systems. To what extent do climatic changes, species extinctions, land use changes, soil degradation or dead zones in the sea matter for the stability of Earth's life-support systems? Are there certain critical limits — for example related to global resource use, levels of pollutants and emissions, or ecosystem depletion — beyond which abrupt changes in the global Earth system will become substantially more likely?

The question of whether or not there are global environmental limits is not new, as evidenced by previously defined concepts and past discussions related to 'safe minimum standards' (Ciriacy-Wantrup, 1952); 'limits to growth' (Meadows et al., 1972); 'critical loads' and 'critical levels' (UNECE, 1979); and 'carrying capacity' (Daily and Ehrlich, 1992). Recently, the *Global risks report 2019* of the World Economic Forum included five environmental risks among the top 10 global risks for both likelihood and impact (WEF, 2019).

Much attention has been paid to climate change — the most well-known example of a human-induced Earth system change process that is already affecting Europe and the world negatively in many ways, e.g. through the increased probability of extreme weather events and associated risks. In addition, potential tipping points in the climate system give rise to serious concerns, i.e. so-called 'tipping elements' in the climate system such as the Greenland ice sheet or the Jetstream (Lenton et al., 2008; Levermann et al., 2012; Hansen et al., 2016; Steffen et al., 2018). The transgression of certain tipping points for these elements could trigger self-reinforcing feedback loops resulting in continued global warming even if human emissions were reduced to almost zero. It has been estimated that several of these tipping elements risk collapsing at temperature increases of between 2 °C and 3 °C, although many uncertainties remain (Schellnhuber et al., 2016; Steffen et al., 2018).

Climate change is intrinsically linked with other essential Earth system processes through numerous feedback loops on multiple scales. The planetary boundaries framework identified nine 'planetary life-support systems' that regulate the stability and resilience of the Earth system and are therefore considered vital for human survival, referred to as 'planetary boundaries' (Rockström et al., 2009; Steffen et al., 2015). The nine planetary boundaries are (1) climate change; (2) change in biosphere integrity (driven by biodiversity loss); (3) stratospheric ozone depletion; (4) ocean acidification; (5) biogeochemical flows, namely interference with the phosphorus and nitrogen cycles; (6) land system change; (7) freshwater use; (8) atmospheric aerosol loading; and (9) introduction of novel entities (details in Chapter 2). The framework proposes precautionary quantitative planetary boundaries, referred to as limits, within which humanity can continue to develop and thrive, also referred to as a 'safe operating space'. The framework suggests that crossing these boundaries increases the risk of generating large-scale abrupt or irreversible environmental changes that could turn the Earth system into a state that is detrimental or catastrophic for human development.

1.2 Policy context for planetary boundaries

Human-caused threats to Earth's life-support systems are increasingly recognised as a reality that requires concerted policy responses, including setting binding targets.

At the **global level**, this is most prominently illustrated by the Paris Agreement adopted by 195 participating member states and including the European Union (UNFCCC, 2015), with the aim of keeping the increase in global average temperature well below 2 °C above pre-industrial levels, preferably below 1.5 °C. The idea of global environmental limits is also reflected in the United Nations 2030 Agenda for Sustainable Development (UN, 2015), which 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. The first Global Sustainable Development Report by the United Nations Secretary-General indicates that:

> The accumulated impacts of human activities on the planet now present a considerable risk of the Earth system itself being changed beyond recognition, with grave consequences for humanity and all life on the planet (UN, 2019, p. 36).

At the **EU level**, the European Commission adopted the reflection paper *Towards a sustainable Europe by 2030*, stating that:

> When implementing the 2030 Agenda, the European Commission and all other stakeholders need to respect key principles, to fulfil existing commitments under international agreements, to commit to a transformation of our social and economic model, to prioritise and fast-track actions for the poorest and most marginalised in society ('leave no one behind'), **to recognise planetary boundaries**, to respect human rights and the rule of law, and ensure policy coherence for sustainable development (EC, 2019c, p. 126).

The EU Seventh Environment Action Programme — the strategic guide for EU environmental policymaking until 2020 — sets out the vision of '**Living well, within the limits of our planet**', which directly relates to the idea of planetary boundaries (EC, 2013). In addition, numerous EU long-term objectives, goals and strategies have been developed — on climate and energy, biodiversity, or soil/land take — that have direct links with Europe's impact on large-scale Earth system processes and thus offer important entry points. The European Commission's recent bioeconomy strategy — *A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment* — also explicitly recognises that:

> A sustainable bioeconomy has a pivotal role in reducing pressures on major ecosystems such as oceans, forests and soils **to a level respecting all planetary boundaries**, and support their pivotal role for balanced nutrient cycles and as carbon sinks (EC, 2018, p. 26).

Most recently, the political guidelines for the European Commission 2019-2024 raised the ambitions further by setting out an agenda for a **European Green Deal** stating that 'Europe must lead the transition to a **healthy planet**.' (EC, 2019a). The follow-up European Green Deal communication comprises numerous initiatives and strong political commitments to address the detrimental impacts of society on Earth's life-support systems, such as climate ('the Commission will propose the first European 'Climate Law' by March 2020. This will enshrine the 2050 climate neutrality objective in legislation'), pollution loads ('a zero pollution ambition for a toxic-free environment') and biodiversity (an ambitious biodiversity strategy for 2030 by leading the world at the 2020 Conference of the Parties to the Convention on Biological Diversity) (EC, 2019b).

In this context, the environmental impacts of EU consumption have been assessed against the planetary boundaries by the Joint Research Centre (JRC) (Sala et al., 2019, 2017). Life cycle-based indicators for calculating the environmental footprint of EU production and consumption by including the supply chains of products were designed and contrasted with life cycle-based planetary boundaries. The assessment highlighted an overshot by the EU in relation to the impacts of climate change and particulate matter.

On the national scale, several European countries have started to embrace the planetary boundaries framework for framing policy action. Sweden was the first country to assess its environmental footprints in the context of planetary boundaries (Nykvist et al., 2013). Germany's 'Integrated Environmental Programme 2030' (BMUB, 2016) highlights that the need to operate within planetary boundaries is a key priority, and Germany also hosted the international conference 'Making the planetary boundaries concept work' in 2017 to reflect on how to operationalise the planetary boundaries framework (Keppner, 2017). In Switzerland, the concept of planetary boundaries is explicitly anchored in the 2016-2019 sustainable development strategy (Swiss Federal Council, 2016), and Switzerland regularly monitors its environmental footprints against planetary boundaries (Frischknecht et al., 2018). In its 2018 environmental report, the Swiss government (Swiss Federal Council, 2018) dedicated the first chapter to planetary boundaries, how Switzerland's resource consumption relates to them and the systemic

implications for nutrition, housing and mobility. The Netherlands Environment Assessment Agency (PBL) is using the planetary boundary concept to support the national implementation of environment-related SDGs (Lucas and Wilting, 2018).

Private companies are also showing an interest the planetary boundaries concept. For example, an initiative ([1]) is ongoing to look at how the textile industry can operate within planetary boundaries and the One Planet Thinking initiative ([2]) helps companies to define sustainable targets in line with Earth's capacity, an ambition that is also supported by the science-based Targets Network ([3]) and the Planetary Accounting Network ([4]). Businesses are also increasingly interested in measuring and reporting their environmental footprints, including their natural capital accounts, but so far a link with planetary boundaries is missing in many cases.

1.3 Operationalising planetary boundaries on sub-global scales

Although the planetary boundaries framework is increasingly used for policy framing on the European and national scales, operationalising the planetary boundaries or 'limits of the planet' at the level of a country or for Europe holds many challenges. For example, what is the specific limit for each planetary boundary that a country or Europe should strive to stay within? How can these limits be calculated? To apply the planetary boundaries framework on sub-global scales (e.g. on the European scale), the challenge of allocating globally defined limits to Europe, to determine the European shares of the global 'safe operating space', needs to be addressed. Such scale matching of planetary boundaries inevitably requires normative choices regarding principles such as fairness, equity, international burden sharing and the right for economic development (Häyhä et al., 2018).

An associated challenge is how to measure — or at least estimate — what the actual European or national performance is against scale-matched European or national shares. Measuring performance against scale-matched European or national shares requires the quantification of pressures on the environment from European or national production and consumption. This can be done from a range of complementary perspectives (EEA, 2013). Most relevant in the context of planetary boundaries is the consumption or footprint perspective, which relates environmental pressures to final demand for goods and services. It takes into account today's globalised economy with trade flows between regions and countries, and includes the total environmental pressures resulting from consumption irrespective of the geographical location where the production of these goods and services has resulted in environmental pressures. Thus, the footprint approach also accounts for the environmental pressures caused around the world by European or a country's domestic consumption.

Over the past decade or so, substantial scientific progress has been made towards quantifying the environmental footprints embodied in internationally traded products through approaches such as multiregional input-output (MRIO) databases (Lenzen et al., 2013; Timmer et al., 2015; Tukker et al., 2016; Cabernard et al., 2019) and trade and life cycle assessment (TRAIL) (Frischknecht et al., 2018). At the JRC, life cycle-based indicators have been developed to quantify the environmental impacts of consumption in the EU, including trade (Sala et al., 2019). The environmental impacts of trade have been assessed based on two complementary approaches: MRIO (Beylot et al., 2019) and process-based life cycle assessment that quantifies the environmental impacts of representative traded products (Corrado et al., 2019). Therefore, improved estimations about the (trends in) environmental impacts of consumption in Europe are now available.

One of the state-of-the-art MRIO models is Exiobase (http://www.exiobase.eu) — developed through the Desire project — a Seventh Framework Programme (FP7) research project funded by the European Commission. The recent release of Exiobase 3.4 (Stadler et al., 2018) provides an excellent and timely opportunity to explore European environmental footprints in the context of planetary boundaries.

1.4 Purpose and coverage of the report

The purpose of this report is twofold.

In step 1, the report aims to explore how the use of different allocation principles would influence the definition of European limits for selected planetary boundaries.

([1]) https://www.stockholmresilience.org/research/research-news/2017-04-04-fashion-within-boundaries.html
([2]) https://www.oneplanetthinking.org/home.htm
([3]) https://www.iiasa.ac.at/web/home/research/twi/190114-SBT.html
([4]) https://www.planetaryaccounting.org

The report builds on and expands previous studies (see Chapter 3). These previous studies defined the European and national shares based on an equality approach, which assumes the basic idea of equal rights for all humans on Earth. This report explores alternative allocation principles to define these shares depending on normative choices regarding aspects of fairness, responsibility (from a historic perspective), capacity to act, international burden sharing and the right for economic development.

In step 2, the report aims to evaluate the extent to which current European environmental footprints are compatible with the European limits defined in step 1.

A state-of-the-art MRIO model is used to calculate European footprints (see Chapter 4). These footprints are compared with the European limits defined in step 1, to assess European performance (see Chapter 5).

The analysis covers the European territory, defined in this report as the combined territory of the 33 member countries of the EEA (the 28 EU Member States plus Iceland, Liechtenstein, Norway, Switzerland and Turkey). Only planetary boundaries quantified on a global scale can be taken into account for such an approach.

In this report, three planetary boundaries/four Earth system processes have been selected for an explorative European-scale analysis: biogeochemical flows (phosphorus and nitrogen cycles, addressed separately in this report), land system change and freshwater use. In addition, a case study for Switzerland on biosphere integrity (genetic diversity) is included.

1.5 Overall report structure

The report is structured as follows.

Chapter 2 provides an overview of the **planetary boundaries framework** and explains which planetary boundaries have been included in the analysis (Section 2.1). It also describes the control variables and the global limits used in this study, as some of them differ from those originally proposed (Steffen et al., 2015) (Section 2.2).

Chapter 3 explores possible **allocation approaches** for scale matching the global limits: Section 3.1 covers theoretical and operational aspects, Section 3.2 implements a selection of computation methods and analyses the resulting European shares, and Section 3.3 applies the European shares for the specific planetary boundaries selected for this study to derive European limits (Section 3.4).

Chapter 4 provides an introduction to **environmental footprint indicators** and their calculation (Section 4.1), and presents the footprint results for Europe and globally (Section 4.2).

Chapter 5 presents the results of the **European performance** calculations in terms of whether the environmental footprints of Europe (as calculated in Chapter 4) are within European limits (as calculated in Chapter 3) for the planetary boundaries selected for this study.

Chapter 6 presents a **case study for Switzerland** on biosphere integrity.

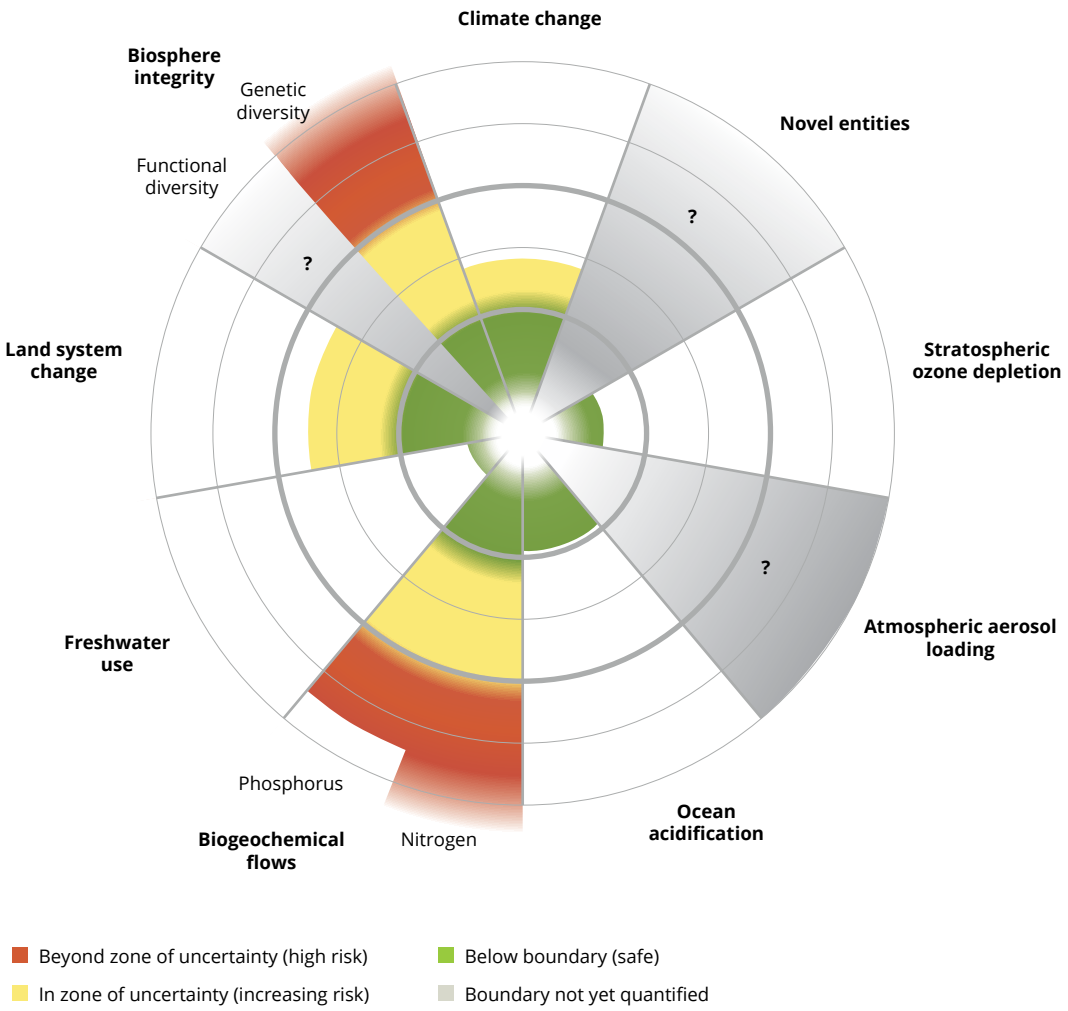
Chapter 7 provides some reflections on the **implications of the findings** for policy (Section 7.1) and knowledge (Section 7.2) development.

2 Using the planetary boundaries framework

2.1 The planetary boundaries framework

As mentioned in Chapter 1, the planetary boundaries framework identified nine planetary life-support systems. They were first introduced by Rockström et al. (2009) and have subsequently been refined by Steffen et al. (2015). For each of the planetary boundaries, so-called 'control variables' have been defined as proxies to measure whether or not they are transgressed on the global scale because of human activities (Rockström et al., 2009; Steffen et al., 2015). Steffen et. al. (2015) suggest that humanity has already transgressed the limits that define a safe operating space for four of the planetary boundaries:

Figure 2.1 The global status of the nine planetary boundaries



Note: The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk) and red indicates the high-risk zone. The planetary boundaries themselves lie at the thick inner circle.

Source: Steffen et al. (2015).

biogeochemical flows (nitrogen and phosphorus cycles) and biosphere integrity (genetic diversity part) (both in the red zone indicating high risk as shown in Figure 2.1), as well as climate change and land system change (both in the yellow zone indicating increasing risk as shown in Figure 2.1). Three planetary boundaries are currently still within the green zone (i.e. the safe operating space): freshwater use, ocean acidification and stratospheric ozone depletion. Some planetary boundaries have not yet been quantified: functional diversity (part of biosphere integrity), novel entities and atmospheric aerosol loading.

There are ongoing scientific discussions on Earth's system processes, and the control variables and limits of the planetary boundaries represent only estimates based on currently available scientific knowledge. Some of the control variables originally proposed by Rockström et al. (2009) were subsequently refined by Steffen et al. (2015). Current control variables and limits are therefore likely to be further refined as knowledge evolves. There is currently no scientific evidence on the magnitude of the impact for some of the issues.

For example, for biosphere integrity there is wide consensus on the rapid rate of change, but there have been few assessments of its consequences (IPBES, 2019). In addition, while some studies assume that a planetary-scale tipping point of the biosphere is plausible (Barnosky et al., 2012), finding suitable indicators and setting limits for biodiversity from a functional perspective are still the focus of intense research (Huitric et al., 2009). Efforts to further define and quantify the biosphere integrity boundary are ongoing (Mace et al., 2014; Newbold et al., 2016). The planetary boundaries framework itself has also been disputed by some scientists (see e.g. Montoya et al. (2018) and the response of Rockström et al. (2018)).

As mentioned by Dao et al. (2018), planetary boundaries cover phenomena with varying spatial scopes. By applying a classification based on biophysical aspects, some can be characterised as truly global phenomena (e.g. climate change, as it is the total amount of greenhouse gas (GHG) emissions that is important, not the location of the emissions), while others are local or regional phenomena the impacts of which can accumulate to a global level (e.g. freshwater use).

To better consider the aggregated processes on a local/regional scale and to prevent the transgression of sub-global boundaries that would 'contribute to an aggregate outcome within a planetary-level safe operating space', Steffen et al. (2015) propose complementing the global limits with sub-global limits for five planetary boundaries: functional diversity (as part of biosphere integrity), phosphorus (as part of biogeochemical flows), land system change, freshwater use and atmospheric aerosol loading.

The remainder of this section provides a brief overview of all nine planetary boundaries.

2.1.1 Biogeochemical flows: nitrogen and phosphorus cycles (assessed in this report)

The biogeochemical boundary is proposed to encompass human influence on biogeochemical flows, covering several elements of relevance for Earth system functioning (Steffen et al., 2015). For now, the focus is on nitrogen and phosphorus, which in this report are addressed as separate boundaries.

Nitrogen cycle

Human activities profoundly influence the nitrogen cycle by converting more N_2 into reactive nitrogen forms than all of Earth's terrestrial processes combined (Rockström et al., 2009). This is primarily through industrial fixation of atmospheric N^2 to ammonia for fertiliser (~80 teragrams of nitrogen (Tg N)/year)), but also via the cultivation of leguminous crops (~40 Tg N/year), fossil fuel combustion (~20 Tg N/year) and biomass burning (~10 Tg N/year) (Rockström et al., 2009).

Much reactive nitrogen eventually ends up in the environment causing eutrophication in the aquatic, marine and terrestrial environments, and may also cause undesired non-linear change in terrestrial, aquatic and marine systems.

Phosphorus cycle

Phosphorus is a finite fossil mineral, mined for use in fertilisers. As a consequence, the addition of phosphorus to regional watersheds happens almost entirely via fertilisers. The original global-level boundary was based on oceanic conditions to reflect the risk of a global ocean anoxic event triggering a mass extinction of marine life, while the additional regional-level phosphorus boundary is designed to avert widespread eutrophication of freshwater systems (Steffen et al., 2015).

2.1.2 Land system change (assessed in this report)

Land system change, driven primarily by agricultural expansion and intensification, contributes to global environmental change, with the risk of undermining human well-being and long-term sustainability. The original control variable defined by Rockström et al. (2009) was the percentage of global land cover

converted to cropland. This was revised by Steffen et al. (2015) to the amount of forest cover remaining in the tropical, temperate and boreal biomes, to better capture those land system changes that directly regulate climate through the exchange of energy, water and momentum between the land surface and the atmosphere.

2.1.3 Freshwater use (assessed in this report)

The global anthropogenic alteration of the freshwater cycle through freshwater withdrawal for human use affects biodiversity, ecological functioning, carbon sequestration and the climate, and therefore potentially also affects the resilience of terrestrial and aquatic ecosystems. The freshwater boundary therefore covers the consumptive use of water from rivers, lakes, reservoirs and renewable groundwater stores. It also includes a basin-scale boundary for the maximum rate of blue water withdrawal along rivers, based on the amount of water required in the river system to prevent regime shifts in the functioning of flow-dependent ecosystems (Steffen et al., 2015).

2.1.4 Biosphere integrity (assessment for Switzerland included in this report)

Human activities have caused consistent wide-spread reductions in species populations and the extent and integrity of ecosystems (IPBES, 2019; UN Environment, 2019). The challenges and impacts of this ongoing loss of biodiversity is underpinned by the increasing body of scientific evidence being synthesised in the context of the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES). In 2020, an ambitious post-2020 global biodiversity framework is foreseen to be adopted in the context of the UN Convention on Biological Diversity to deal with these challenges.

Genetic diversity (part of the biosphere integrity boundary) is discussed in the context of a case study from Switzerland but is not quantified for Europe. Functional diversity (also part of the biosphere integrity boundary) is not assessed here because no global limit has yet been published.

2.1.5 Climate change (not assessed in this report)

The challenge of anthropogenic climate change caused by GHG emissions and associated risks and impacts is underpinned by a huge body of scientific evidence and about four decades of formalised international scientific collaboration through the Intergovernmental Panel on Climate Change (IPCC). Climate change is one of the two core boundaries that are strongly interlinked with the other boundary processes (Steffen et al., 2015). The boundary is considered beyond a safe operating space by Steffen et al. (2015) estimate that the climate change boundary has been crossed.

The international community recognises that serious climate change mitigation is needed and, in 2015, the Paris Agreement made within the United Nations Framework Convention on Climate Change (UNFCCC) was adopted by 195 participating member states including the European Union, with the aim of keeping the increase in global average temperature well below 2 °C above pre-industrial levels, preferably below 1.5 °C.

2.1.6 Ocean acidification (not assessed in this report)

Ocean acidification is the ongoing decrease in the pH of Earth's oceans, caused by the uptake of carbon dioxide (CO_2) from the atmosphere. Ocean acidification is therefore coupled with climate change, as it shares the same primary driver — anthropogenic CO_2 emissions.

2.1.7 Stratospheric ozone depletion (not assessed in this report)

Stratospheric ozone filters ultraviolet radiation from the sun and the thinning of the stratospheric ozone layer has negative impacts on marine organisms and poses risks to human health. Stratospheric ozone depletion is not assessed in this report because it has already been addressed with notable, if not complete, success by actions taken as a result of the Montreal Protocol on Substances that Deplete the Ozone Layer (for chlorofluorocarbons (CFCs), which specified a halt in ozone-depleting emissions.

2.1.8 Atmospheric aerosol loading (not assessed in this report)

Aerosols — small airborne particles either emitted into the atmosphere or formed in the atmosphere from reactive gas emissions — alter many different physical and chemical processes. Human activities since the pre-industrial era have doubled the global concentration of most aerosols. Atmospheric aerosol loading is considered an anthropogenic global change process with the need for a potential planetary boundary for two main reasons: (1) the influence of aerosols on the climate system and (2) their adverse effects on human health on regional and global scales.

However, since there is currently no published global limit this boundary is not considered in this report.

2.1.9 Novel entities (not assessed in this report)

The novel entities planetary boundary addresses newly developed substances that have the capacity to fundamentally disrupt the biophysical functioning of the Earth system on a planetary scale (MacLeod et al., 2014; Persson et al., 2013; Steffen et al., 2015). These may be physical or biological substances — new regimes of radiation and radioactivity, or bioengineered life-forms — but the main class of entities in relation to which globally systemic risks have already been experienced are chemical substances (Amiard-Triquet et al., 2015; Thornton, 2000). However, since no global limit has been published this boundary is not considered in this report.

2.2 Selection of control variables and calculation of global limits

For the purpose of measuring European performance against planetary boundaries (i.e. comparing European limits with European footprints), the biophysical control variables for some of the planetary boundaries proposed by Steffen et al. (2015) have been amended for this study to make them compatible with European footprint data (Chapter 4). Therefore, as in Dao et al. (2015, 2018) — who assessed Switzerland's performance against planetary boundaries — some of the names of the control variables in this report are different from those proposed by Steffen et al. (2015) to represent this change of perspective (see Table 2.1). This also means that the global performances computed are different from the performances reported in Steffen et al. (2015).

Table 2.1 Summary of the control variables and global limits in this report compared with those of the planetary boundaries framework

Planetary boundary	Control variable(s) in Steffen et al. (2015)	Control variable in this report *(compatible with European footprint data)*
Biogeochemical flows: nitrogen cycle	Industrial and intentional biological fixation of nitrogen per year **Global limit:** 62 Tg N/year (62-82 Tg N/year).	Loss of nitrogen from agriculture per year **Global limit:** 28.5 Tg N/year
Biogeochemical flows: phosphorus cycle	**Global:** phosphorus flow from freshwater systems into the ocean per year **Global limit:** 11 Tg P/year (11-100 Tg P/year) **Regional:** phosphorus flow from fertilisers to erodible soils	Loss of phosphorus from agriculture and waste water per year **Global limit:** 0.92 Tg P/year
Land system change	**Global:** area of forested land as a percentage of original forest cover **Global limit:** 75 % (75-54 %) **Biome:** area of forested land as a percentage of potential forest cover	Area of anthropised land **Global limit:** 19 400 000 km^2
Freshwater use	**Global:** maximum amount of consumptive blue water use per year **Global limit:** 4 000 km^3/year (4 000-6 000 km^3/year) **Basin:** blue water withdrawal as a percentage of mean monthly river flow	Maximum amount of consumptive blue water use per year **Global limit:** 4 000 km^3/year

Note: Tg N, teragrams of nitrogen; Tg P, teragrams of phosphorus.

([5]) Based on personal communication with the lead author of de Vries et al. (2013), their original value was modified for the current study.

2.2.1 Biogeochemical flows: nitrogen cycle

Steffen et al. (2015) used 'industrial and intentional biological fixation of nitrogen' as a control variable, while Dao et al. (2015, 2018) proposed a control variable related to nitrogen losses from agriculture, which takes into account both leaching to water and releases of NH_3 to air.

As in Steffen et al. (2015), the selected global limit for this study is taken from de Vries et al. (2013) ([5]), who computed three different limits for nitrogen concentrations in freshwater: nitrogen run-off, NH_3 and N_2O. From there, they derived three related nitrogen losses and three intended nitrogen fixations. However, to be compatible with Exiobase 3.4 the current study uses nitrogen losses, while Steffen et al. (2015) selected nitrogen fixation as a control variable. Thus, the global precautionary limit for this study's control variable (28.5 Tg N/year) differs from the limit computed by Steffen et al. (2015) (62-82 Tg N/year). Despite the difference in this control variable, the same scope is covered as in Steffen et al. (2015).

2.2.2 Biogeochemical flows: phosphorus cycle

Steffen et al. (2015) used two control variables for phosphorus: the quantity of phosphorus flows into the oceans as a global control variable and 'phosphorus flows from fertilisers to erodible soil' as a regional control variable. Dao et al. (2015, 2018) proposed a global control variable in terms of phosphorus releases from agricultural activities.

This study follows Dao et al. (2015, 2018), but takes into account phosphorus losses from urban waste water in addition to the phosphorus releases from agricultural activities. Moreover, the global precautionary limit for phosphorus losses has been modified to make it compatible with the global limit proposed by Steffen et al. (2015) and computable using Exiobase 3.4. The global limit in terms of releases of phosphorus from agriculture and waste water is computed as follows. First, the proportion of the global phosphorus footprint due to releases from agriculture and waste water is computed as the ratio of phosphorus release computed using the Exiobase 3.4 database (for 2011) (1.8 Tg P/year) to the global footprint proposed by Steffen et al. (2015) (22 Tg P/year). Second, this ratio is applied to the limit proposed by Steffen et al. (2015) (11 Tg P/year) to compute a global limit of 0.92 Tg P/year in terms of releases from agriculture and waste water.

The focus on phosphorus releases from agriculture and waste water means that only about 10 % of the limit proposed by Steffen et al. (2015) is taken into account here, hence the limit is about 10 times lower. Despite the difference in the order of magnitude of the control variables, the same scope is covered here as in Steffen et al. (2015). It should be noted that the limit of 11 Tg P/year as proposed by Steffen et al. (2015) is associated with a substantial range of uncertainty (from 11 to 100 Tg P/year). Other global estimations are 17-32 Tg/year (Carpenter and Bennett, 2011) and 8.6 Tg P/year (Seitzinger et al., 2010).

2.2.3 Land system change

Steffen et al. (2015) used two control variables in terms of forested area. One at the global level, 'area of forested land as percentage of original forest cover', and the other at the biome level, 'area of forested land as percentage of potential forest cover'. Rockström et al. (2009) originally proposed the control variable 'percentage of global land cover converted to cropland'.

Dao et al. (2015, 2018) followed the original proposal by Rockström et al. (2009) and extended the type of land cover considered. They used a control variable, 'anthropised land area', which enables a link with socio-economic activities to be established in a robust way: the surface of anthropised land including agricultural (arable land and permanent crops) and urbanised (sealed) land, as percentage of ice-free land excluding water bodies. This study follows the approach of Dao et al. (2015, 2018), with a global limit of 19 400 000 km^2 of anthropised land area. This estimate is associated with some uncertainty, as the degree of human disturbance to the natural system (e.g. intensive versus extensive or organic agriculture) is not considered in the definition of 'anthropised land area', because of data availability constraints. Nevertheless, land system change is a very important issue as is widely recognised, e.g. in assessments by IPBES (IPBES, 2018) and the IPCC (IPCC, 2019).

2.2.4 Freshwater use

Steffen et al. (2015) used two control variables in terms of freshwater use. One at the global level, 'maximum amount of consumptive blue water use (in km^3 per year)', and the other at the basin level, 'blue water withdrawal as percentage of mean monthly river flows'. This study uses the global control variable proposed by Steffen et al. (2015), i.e. 4 000 km^3 per year.

3 Defining a safe operating space for Europe

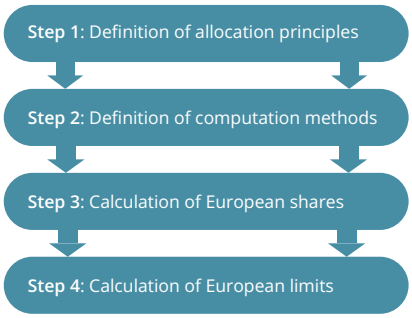
As mentioned in Section 1.3, to apply the planetary boundaries framework on sub-global scales (e.g. on the European scale), the challenge of allocating shares of globally defined limits to Europe, to determine the European shares of the global 'safe operating space', needs to be addressed. Such scale matching of planetary boundaries is inevitably associated with normative choices regarding aspects of fairness, equity, international burden sharing and the right for economic development.

Several studies have applied the planetary boundaries framework on sub-global scales by defining limits based on an equality approach — which assumes the basic idea of equal rights for all humans on Earth. This approach means that shares on a sub-global scale are calculated simply as a function of a region's or a country's share of the global population. Results from such an approach first became available for Sweden (Nykvist et al., 2013), then for the EU (Hoff et al., 2014) and Switzerland (Dao et al., 2015, 2018), and, most recently, for a wide range of countries worldwide (http://www.bluedot.world; O'Neill et al., 2018).

These studies provide valuable initial insights on the allocation of planetary boundaries, but they all employ an equality approach or a variant thereof. However, the negotiations regarding climate change in the context of the United Nations Framework Convention on Climate Change (UNFCCC) offer a large number of examples of how the notions of equity and fairness could be implemented in international environmental policy. Recently, a Dutch study experimented with calculation approaches other than those based on equality: the authors evaluated how a 'basket' of different allocation principles would affect the definition of a safe operating space for the Netherlands (Lucas and Wilting, 2018).

In the current study, the evaluation of different allocation principles is extended to the European scale. The scale matching of planetary boundaries distinguishes four steps (Figure 3.1). Theoretical aspects in terms of allocation principles are covered in Section 3.1. Possible ways to operationalise these principles (using various computation methods) are discussed in Section 3.2. The application of steps 1 to 2 to derive European shares, independent of any planetary boundary, is then described in Section 3.3. Finally, in Section 3.4, the European shares calculated are applied to the three planetary boundaries/four Earth system processes considered in this study to derive European limits.

Figure 3.1 Scale matching of planetary boundaries in four steps



Source: EEA/FOEN.

3.1 Definition of allocation principles

The starting point for scale matching, so that the planetary boundaries framework can be applied on sub-global scales, is the recognition that natural resources are needed for three main reasons: inputs (energy and resource bases), sinks (energy, heat, pollutants) and ecosystem services (e.g. forests provide, among other things, wood and recreational areas). Thus, keeping human activity within planetary boundaries can be considered essential for maintaining a global common property resource or a public good. The term 'global commons' refers to international, supranational and global resource domains, and includes Earth's shared natural resources, such as the high oceans and the atmosphere. For a discussion of public goods and global commons, see for example Harris and Roach (2017).

Multiple resource-sharing schemes have been designed over the years to enable the sound management of common goods. Two overarching logics have been applied: right to use (resource sharing) and duty

to conserve (effort sharing) (IPCC et al., 2014). With respect to climate change, the Intergovernmental Panel on Climate Change (IPCC) (2014) mentions that 'the resource-sharing frame is the natural point of departure if climate change is posed as a tragedy of the commons type of collective action problem; if it is posed as a free-rider type of collective action problem, the effort-sharing perspective is more natural. Neither of these framings is thus objectively the "correct" one'.

It should be noted that rights and duties can have different bases, e.g. religious, moral, political or legal. The report discusses the potential principles that could be applied in a situation where such rights and duties would be accepted, but does not discuss their potential bases. Moreover, allocation principles are normative concepts. This report does not make any judgement on which allocation principle should or should not be applied (alone or in combination).

International climate negotiations represent a unique example of systematic public discussions about the global allocation of rights to use resources or duties to conserve them. These discussions led to the concepts of equity and differentiation (Rose et al., 1998). Originating from the Earth Summit (held in Rio de Janeiro in 1992), the 'Common But Differentiated Responsibilities' principle is central in international environmental politics. This principle, enshrined in legal agreements such as the UNFCCC, holds that, although all countries have a responsibility in the achievement of common goals, each country may be required to make different efforts depending on its past or current contribution to environmental degradation, as well as on its capability to act.

Since the 1990s, more than 40 studies have proposed ways of quantitatively operationalising this central principle to allow sharing schemes to be devised, or greenhouse gas (GHG) emission allowances or reductions to be calculated at national or regional levels in a fair and equitable way (Höhne et al., 2014). Each of these studies considers a specific aspect of how to allocate efforts required, e.g. historical trajectories of countries/regions, development needs, responsibility, capacity, equality, sovereignty or efficiency (Höhne et al., 2014; IPCC et al., 2014; Häyhä et al., 2018).

This study builds on two existing synthetic classification systems of the main allocation principles. The first classification was proposed by Höhne et al. (2014) and considers the following: (1) responsibility (concerns historical contributions to global emissions or warming); (2) capability (also called 'capacity' or 'ability to pay for mitigation'); (3) equality (equal rights per person, immediately or over time); and (4) cost effectiveness.

The second classification system, proposed by Sabag Muñoz and Gladek (2017), based on Shue (1999), discusses four categories of approaches for allocating planetary boundaries at country and company levels: (1) egalitarian approaches; (2) economic throughput; (3) economic capacity and efficiency; and (4) historical justice and inertia (including polluters pays and grandfathering principles).

This study extends these classifications in three ways. First, allocation principles are grouped into two categories: (1) those that consider people as the recipients of the allocation of resources or of the allocation of duties; and (2) those that consider countries as the recipients. Second, 'sovereignty' is taken into account explicitly. 'Sovereignty' is mentioned as a staged category by Den Elzen and Lucas (2005), Höhne et al. (2014), and Lucas and Wilting (2018). Third, 'capability' (ability to pay) is distinguished from 'needs' and there is a further distinction between 'right to development' and 'needs' (related to personal aspects such as age or household structure).

Figure 3.2 gives an overview of the allocation principles taken into account. The attribution of the allocation principles to people or countries is based on which associations seem most natural. This means that 'equality', 'needs' and 'right to development' usually refer to people, while 'sovereignty', 'capability' and 'responsibility' are normally discussed at the level of countries. Definitions are provided for these allocation principles in Table 3.1.

It should be noted that other frameworks could have been applied. Rose et al. (1998), for example, classified alternative equity criteria for global warming policy into three categories. The first category, 'allocation-based', focuses on the rules for the allocation of the rights (e.g. every country has the same rights). The second category, 'outcome-based', considers the equity resulting from the allocation (e.g. no nation should be worse off), while the third category, 'process-based', considers the manner in which decisions are made (e.g. whether or not the negotiation process is fair).

Figure 3.2 Schematic overview of allocation principles applied in this study

Source: EEA/FOEN.

Table 3.1 Short description of allocation principles applied in this study

Allocation principle	Description
A. Equality	People have equal rights to use resources, resulting in an equal share per capita. Equality can be envisaged among people living in a particular year or among people over time.
B. Needs	People have different resource needs. This could be because of their age, the size of the household they live in or their location. As a result, their right to resources could also be different.
C. Right to development	People have the right to have a decent life (e.g. the right to cover basic needs). In the long term, a convergence of welfare among people could be envisaged. People in countries with lower development levels could thus be allocated more resources or contribute less to mitigation efforts to enable development objectives to be met.
D. Sovereignty	Other than in relation to engagements in international treaties, countries are managed based on internal policy rules. Countries have a legal right to use their own territory as they choose. In addition, countries have different levels of economic wealth and environmental impacts (generated domestically and in foreign economies). This situation is accepted as a starting point for allocating the global budget on national scales (e.g. by grandfathering).
E. Capability	Countries have different levels of economic wealth. Countries with higher financial capabilities could contribute proportionally more to mitigation efforts or use less than their allocated share of resource, since their ability to pay is higher.
F. Responsibility **(not applied in this report)**	Countries have used resources in the past. It is thus possible to consider a date in the past to compute the remaining current rights. This principle can be applied for only two planetary boundaries, 'climate change' and 'ocean acidification', for which budgets can be calculated over time. Thus, this principle has not been applied in this study.

Another principle is cost effectiveness, which deals with techno-economic considerations for the management and optimisation of resource use. Such an allocation can be based on economic objectives, e.g. the equalisation of the marginal costs of mitigation among countries, or on technical aspects. In terms of reductions, priority should then be given to countries or sectors with higher or more cost-effective potential for reduction. However, as this principle is difficult to quantify and has been developed only for climate change, it is not considered in this report.

3.2 Definition of computation methods

The operationalisation of the allocation principles aims to generate quantitative results. However, not all planetary boundaries can be considered in the same way because they differ in terms of their current global status (i.e. whether there is an overshoot of the boundary or not). Some planetary boundaries, such as climate change, have already been overshot and bringing them back into a safe operating space requires sharing a mitigation burden. This however is not the case for other planetary boundaries, such as freshwater use, for which sharing responsibilities relates not to burdens but to rights to use current resources.

In addition, the current scientific understanding and modelling outputs vary across the different planetary boundaries. Current scientific understanding of climate change is more advanced than for other planetary boundaries. For example, the modelling of pathways, as well as scenarios of possible trajectories (as developed by the IPCC or the International Energy Agency (IEA) for climate change), are not available for the other planetary boundaries. Pathways enable the role of policies, technical and economic aspects to be taken into account and can thus be considered a more realistic way of illustrating a trajectory from current resource use to reduced use in the future than using budgets only.

However, except for climate change and ocean acidification, the current scientific knowledge base does not allow the concept of pathways to be meaningfully applied. As a result, as mentioned in Section 3.1, past methods of operationalising, for the purpose of

allocating the global limits of planetary boundaries to countries and regions, have employed a simple equality approach, i.e. by considering an equal share per capita of the global population for a fixed year without any consideration of the needs of future populations.

A slightly more advanced application of the equality principle, combined with the responsibility principle, is found in Dao et al. (2015, 2018), who employed a two-stage allocation: first to people (based on an equal share per capita) and then to countries (by adjusting the country shares over time to the year 2100 based on population projections). The most systematic application of various allocation principles is found in a recent study for the Netherlands (Lucas and Wilting, 2018).

In this report, for the planetary boundaries analysed on the European scale, five out of the six **allocation principles** introduced in Section 3.1 are taken into account. Three of them relate to allocations to people (equality, needs and right to development) and two to allocations to countries (sovereignty and capability). The principle of responsibility is applicable to only the planetary boundaries of climate change and ocean acidification – for which budgets can be calculated over time – and is therefore not considered further.

For each of the five allocation principles, multiple (at least two) **computation methods** have been applied, to ensure a broad range of perspectives in the calculation of the different shares for Europe and thus to effectively represent the different normative choices associated with allocating global planetary boundaries to the European scale. The allocation principles and computation methods are considered one by one in this report. They could however be combined in different ways, since there is no exclusive relationships between them. In total, 13 computation methods were selected across the five allocation principles (Table 3.2).

For each computation method, an **allocation key**, used as the basis for performing the allocation, has been defined. The allocation keys can be either drivers of environmental impacts, according to the IPAT formula (i.e. expressing environmental **i**mpact as a product of three factors: **p**opulation, **a**ffluence and **t**echnology), or any other relevant key such as a specific environmental impact, land area or development level. Each allocation key is quantified by a **specific indicator**; for example, the Human Development Index (HDI) is used as an indicator for the 'Population weighted by HDI' allocation key.

In some cases, a **transformation function** (e.g. a logarithmic transformation) has been applied to indicators to eliminate data outliers, or to adjust saturation levels in relation to poverty or luxury thresholds beyond which the influence of the variable is considered constant. Where information is available for setting thresholds, linear relationships have been complemented with saturation points.

With respect to **time**, some computation methods are repeated for multiple reference years (e.g. 1990, 2000 and 2011). No assumptions are made about trajectories or pathways of resource use in the future (as is the case for many allocation methods described in the climate change literature). All of the computation methods quantify the European allocation/share of the global limit.

Further information on the computation methods, including on the choices of indicators, transformation functions, time (use of different scenarios) and data sources, is provided in Annex 1. These 13 computation methods are considered sufficient to represent the different normative choices associated with the allocation of global planetary boundaries to the European scale, but they are not an exhaustive list. Many additional approaches could be applied, based on different allocation keys, data sets, years/choices of time periods or mathematical calculation methods.

Past studies have shown that the possible differences resulting from the modification of computation methods and allocation keys when calculating shares for a specific allocation principle can be as a large as when switching between allocation principles. For example, by comparing GHG sharing schemes, Höhne et al. (2014) concluded that, 'within specific categories of effort sharing, the range of allowances can be substantial. The outcome is often (and to a larger extent) determined by the way the equity principle is implemented rather than anything to do with the equity principle itself'.

Table 3.2 Allocation principles, computation methods and allocation keys

Allocation principles and computation methods	Allocation key	Description
A. Equality		
1. Equal share per capita	Population	Allocation to people then to countries proportionally with respect to their share of the global population
2. Equal share per capita over time	Cumulative population	Allocation to countries proportionally with respect to their cumulative share of the global population
B. Needs		
3. Equivalence between adults and children	Population weighted by age	Allocation to people then to countries proportionally with respect to their share of the global population, considering differences, in terms of needs, between adults and children
4. Accessibility	Travel time to major cities	Allocation to people then to countries proportionally with respect to their share of the global population, considering differences in terms of accessibility
5. Nutrition	Food nutrient adequacy	Allocation people then to countries proportionally with respect to their share of the global population, considering differences in terms of nutrition levels
C. Right to development		
6. Poverty line	Poverty headcount ratio	Allocation to people then to countries proportionally with respect to their share of the global population below a certain level of income
7. Development level	Population weighted by HDI	Allocation to people then to countries proportionally with respect to their development needs as indicated by the HDI
D. Sovereignty		
8. Land	Territorial land surface	Allocation to countries proportionally with respect to their territorial share of the global land surface
9. Biocapacity	Territorial biocapacity	Allocation to countries proportionally with respect to their territorial share of global biocapacity
10. Economic throughput	GDP	Allocation to countries proportionally with respect to their share of the global economic throughput (GDP)
11. Grandfathering	Consumption-based environmental impacts	Allocation to countries proportionally with respect to their share of global environmental impacts (from a consumption perspective), i.e. grandfathering
E. Capability		
12. Income	Inverse GDP	Allocation to countries by considering an inverse proportional relationship with respect to their share of global income (inverse GDP)
13. Cumulative income	Inverse cumulative GDP	Allocation to countries by considering an inverse proportional relationship with respect to their share of cumulative global income (inverse cumulative GDP)

Note: GDP, gross domestic product.

3.3 Calculating European shares

A summary of the European shares ([6]) of global limits calculated for 2011 is provided in Table 3.3. Median and average values are based on the number of calculations mentioned in the table. The year 2011 was chosen as the reference year because of the availability of corresponding footprint data (see Chapter 4). Median and average values were calculated step by step to account for the different numbers of computation methods used and calculations performed for each principle. First, if applicable, these values were calculated for each of the computation methods considering the different calculations performed for

([6]) The analysis covers the European territory, defined in this report as the combined territory of the 33 member countries of the EEA (the 28 EU Member States plus Iceland, Liechtenstein, Norway, Switzerland and Turkey).

Table 3.3 Summary of European shares (for 2011) grouped by allocation principle

Allocation principles and computation methods	Number of calculations	Minimum European share	Average	Median	Maximum European share
A. Equality	9	6.2 %	8.1 %	8.1 %	10.2 %
1. Equal share per capita	3	8.4 %	9.3 %	9.2 %	10.2 %
2. Equal share per capita over time	6	6.2 %	7.0 %	6.9 %	7.8 %
B. Needs	4	3.3 %	7.1 %	7.3 %	9.2 %
3. Child/adult equivalence	1	n/a	n/a	9.2 %	n/a
4. Accessibility	2	3.3 %	5.0 %	5.0 %	6.7 %
5. Nutrition	1	n/a	n/a	7.3 %	n/a
C. Right to development	3	2.7 %	4.1 %	4.1 %	5.1 %
6. Poverty line	1	n/a	n/a	5.1 %	n/a
7. Development level	2	2.7 %	3.2 %	3.2 %	3.6 %
D. Sovereignty	5	4.3 %	11.4 %	12.5 %	21.0 %
8. Land	1	n/a	n/a	4.3 %	n/a
9. Biocapacity	1	n/a	n/a	10.6 %	n/a
10. Economic throughput	2	11.2 %	16.1 %	16.1 %	21.0 %
11. Grandfathering	1	14.4 %	14.4 %	14.4 %	14.4 %
E. Capability	6	3.8 %	5.9 %	6.2 %	7.5 %
12. Income	3	3.8 %	5.4 %	5.7 %	6.5 %
13. Cumulative income	3	5.0 %	6.4 %	6.7 %	7.5 %
All	**27**	**2.7 %**	**7.3 %**	**7.3 %**	**21.0 %**

Note: The calculations for computation methods 8 (land) and 9 (biocapacity) refer to the years 2010 and 2013, respectively.

each method (e.g. due to multiple reference years), then, for each allocation principle, by applying an equal weighting for each of the computation methods. Eventually, they were calculated for all allocation principles to derive overall European median and average values. For cases in which only a single value was calculated (e.g. for 'Child/adult equivalence' or 'Nutrition'), this value is shown in the table as the median. The discussion below considers only the median values unless otherwise indicated. For details of these computations, see Annex 1.

The application of these five allocation principles, by performing a total of 27 different calculations, results in an overall median European share of 7.3 % of the global limit.

3.3.1 Equality principle

For the equality principle, the median value is 8.1 %. The value based on equal share per capita (computation method 1) diminishes over time (going from 10.2 % in 1990 to 8.4 % 2011) because the European share of the world population is decreasing. The smallest value represents the latest year. The equal share per capita over time method (computation method 2) results in a lower European share compared to computation method 1 (ranging from 7.8 % to 6.2 %) depending on the choice of the start and end years (i.e. 1990, 2000 or 2011 as the start year and 2050 or 2100 as the end year).

3.3.2 Needs principle

If the needs principle is used, the median value for Europe is lower than if the allocation is based on the equality principle: 7.3 % rather than 8.1 %. While considering equivalence between children and adults (computation method 3) results in a higher European share than the median value based on the equality principle (9.2 % compared with 8.1 % for 2011), since the proportion of adults is higher in Europe than in the rest of the world, this is not the case for the other two computation methods. If the accessibility method is used (computation method 4), the European median value is lower than that based on the equality principle,

since there is a higher level of accessibility in Europe than in the rest of the world. The same is true for an allocation that considers nutrition (computation method 5).

3.3.3 Right to development principle

Considering the right to development principle results in the lowest share for Europe (4.1 %) of all the principles used for allocation. This is because European development levels (measured by the poverty line and the HDI) are higher than in the rest of the world. The method based on the poverty line (computation method 6) results in a European share of 5.1 %. The result of an additional extreme scenario (see Section 3.2.1 for a description of computation method 6) is not included in Table 3.3. Considering the development level (HDI) (computation method 7) results in the lowest value of all the European allocations considering people (2.7 % to 3.6 %), since the HDI is higher in Europe than in the rest of the world.

3.3.4 Sovereignty principle

Considering the sovereignty principle results in the highest share for Europe (12.5 %) of all the principles used for allocation (when considering median values). Based on median values, the European share is relatively low if the land surface method (computation method 8) is used (4.3 %) but higher if biocapacity (computation method 9) is considered (10.6 %). The value is even higher if economic throughput (computation method 10) (between 11.2 % (log function to attenuate extreme values) and 21 % (linear function)) or Grandfathering (computation method 11) (14.4 %) (i.e. assuming a similar reduction per region) is considered. These high European shares reflect the assumption, in accordance with this principle, that Europe's relative economic strength necessitates its proportionally greater use of the global commons.

3.3.5 Capability principle

Applying the capability principle results in a lower share for Europe (6.2 %) than an allocation based on the equality principle (when considering median values). An allocation based on income (computation method 12) reduces the European share, to between 3.8 % and 6.5 %, while the value is between 5.0 % and 7.5 % if cumulative income (computation method 13) is considered. This low European share reflects the fact that Europe has a relatively large income and can thus incur more costs or use fewer resources.

3.3.6 Concluding remarks

Most previous studies exploring the planetary boundaries framework on sub-global scales have applied the equality principle, i.e. a simple 'equal share per capita' computation method. Compared with this, the application of other allocation principles reduces the European share except when applying the principle of sovereignty (i.e. an allocation principle with a strong emphasis on economic aspects).

There are several options for setting a reference value for the European share. Setting a reference European share equivalent to the median share, derived by considering all allocation principles, would result in a European share of 7.3 %. Another possibility would be to consider only the most recent data when calculating the share rather than considering various years as has been done for this report.

3.4 Results — European limits

The European shares for the year 2011 (i.e. the year for which the most recent reported footprint data are available from Exiobase; see Chapter 4) are used to calculate European limits for the three planetary boundaries/four Earth system processes selected for this study: biogeochemical flows — nitrogen cycle and phosphorus cycle (separate calculations); land system change; and freshwater use. This means that, for each planetary boundary, the percentage shares presented in Table 3.3 (minimum, average, median and maximum values) are applied to the global limit values (in Table 2.1), resulting in limits for each planetary boundary on the European scale (see Table 3.4 for absolute values and Table 3.5 for per capita values).

Table 3.4 European limits for selected planetary boundaries based on five allocation principles (absolute values)

Planetary boundary		European limit			
Name	**Control variable**	**Minimum**	**Average**	**Median**	**Maximum**
Biogeochemical flows: nitrogen cycle	Loss of nitrogen from agriculture per year (Tg N/year)	0.8	2.1	2.1	6.0
Biogeochemical flows: phosphorus cycle	Loss of phosphorus from fertilisers and waste per year (Tg P/year)	0.03	0.06	0.07	0.19
Land system change	Anthropised land (10^6 km^2)	0.5	1.4	1.4	4.1
Freshwater use	Blue water consumption (km^3)	110	280	291	840

Notes: The value for each control variable is based on a total of 27 computations, reflecting the five allocation principles and the associated computation methods used.

Tg N, teragrams of nitrogen; Tg P, teragrams of phosphorus.

Table 3.5 European limits for selected planetary boundaries based on five allocation principles (per capita values)

Planetary boundary		European limit			
Name	**Control variable**	**Minimum**	**Average**	**Median**	**Maximum**
Biogeochemical flows: nitrogen cycle	Loss of nitrogen from agriculture per year (kg N/year)	1.3	3.5	3.5	10.1
Biogeochemical flows: phosphorus cycle	Loss of phosphorus from fertilisers and waste per year (kg P year)	0.04	0.11	0.11	0.32
Land system change	Anthropised land (m^2)	894	2 385	2 364	6 832
Freshwater use	Blue water consumption in (m^3)	185	471	488	1 411

Notes: The value for each control variable is based on a total of 27 computations.

Kg N, kilograms of nitrogen; kg P, kilograms of phosphorus.

4 European and global environmental footprints

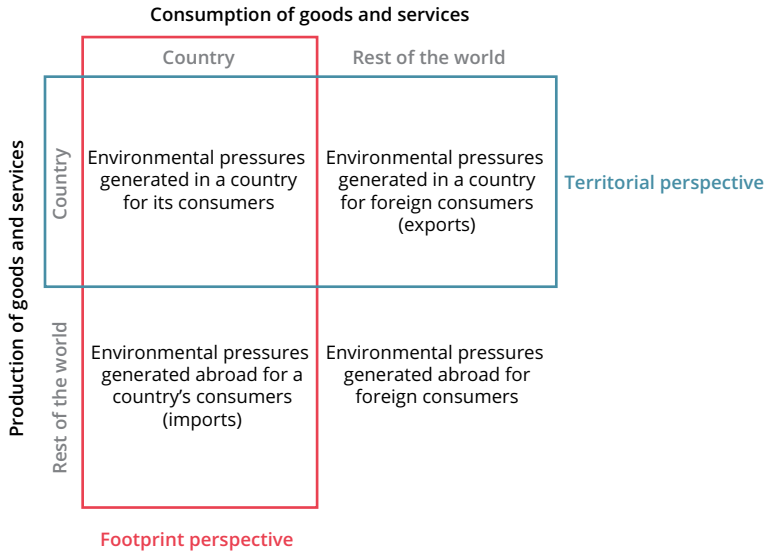
4.1 Generating environmental footprint indicators

Environmental footprint indicators are different from traditional territorial environmental indicators at country level (see Figure 4.1). Territorial indicators consider emissions or environmental pressures occurring in the territory of a country, e.g. the domestic greenhouse gas emissions reported under the Kyoto Protocol. In contrast, footprint indicators (also named consumption-based indicators) relate environmental pressures and/or resource use to the final demand for goods and services. They therefore allow the total environmental pressures resulting from the consumption of the inhabitants of a country to be quantified regardless of where on Earth the production of these goods and services has caused environmental pressures.

A footprint perspective is increasingly relevant in today's interlinked global economy: because of growing international trade, more and more of the environmental impact on a territory is generated to satisfy consumers in other countries. For most developed economies, more than half of the environmental impact induced by their consumption is thus exerted elsewhere in the world (Dao et al., 2015). Europe is also highly dependent on resources extracted from or used outside Europe, such as water, land use products, biomass or other materials, to meet its relatively high consumption levels. This means that a large part of the environmental impact associated with European consumption is exerted in other parts of the world.

Some environmental footprints have their basis in environmentally extended input-output (EEIO) models. These are economic-environmental models that provide economic and environmental information at country, industry and generic product levels. They are built by combining economic information from national accounts (input-output tables) (Eurostat, 2008) with environmental information per industry. They thus provide a coherent account of the total environmental footprint of a country and of the average direct environmental footprint of its industries. Such country

Figure 4.1 Territorial and footprint perspectives



Source: Adapted from Dao et al. (2015).

models can be extended to build global models: environmentally extended multiregional input-output (MRIO) models. These describe inter-industrial relationships on the global scale and integrate the full production, trade and consumption linkages between industries and countries, following the inter-regional input-output (IRIO) philosophy (Miller and Blair, 2009).

MRIO models enable footprints to be computed that link:

- all economic activities required for producing a particular good in a specific country, accounting for international trade;
- all emissions of pollutants and uses of resources induced by these economic activities wherever they occur;
- the country where a good will be finally consumed by a household with the countries where production activities occurred in the supply chain.

Substantial scientific progress has been made over the past decade to quantify the environmental footprints embodied in internationally traded products through MRIO approaches (Lenzen et al., 2013; Timmer et al., 2015; Tukker et al., 2016) or life cycle assessment bottom-up approaches that quantify the environmental impacts of single representative traded products (Frischknecht et al., 2018; Corrado et al., 2019). Some studies have employed a combination of both approaches, such as a study by the Joint Research Centre (JRC) on the environmental impacts of EU production and consumption (Sala et al., 2019).

A footprint perspective is particularly relevant in the context of the globally defined planetary boundaries framework. The current study employs footprint indicators, computed with the most recently released public MRIO model, Exiobase 3.4 (Stadler et al., 2018), which can be considered a state-of-the-art MRIO model.

Multiple MRIO models exist and each has different strengths and limitations related to factors such as the extent of the use of official statistics, the range of available environmental extensions and the level of disaggregation (see www.environmentalfootprints.org/databases/ for descriptions and documentation). The choice of the most appropriate model is strongly related to the aims and scope of the analysis. For the calculation of European performance against the three planetary boundaries for this study, Exiobase 3.4 was used. It is considered robust and has the range of environmental extensions necessary to allow its application to all three planetary boundaries/four Earth system processes, as well as the necessary level of disaggregation. Footprints were calculated for the years 1995-2011, which is the time series of reported data in Exiobase 3.4, the most recent version, released in 2018. Data for beyond the year 2011 are only estimated in Exiobase 3.4 and have therefore not been included in this study.

Specific care has been taken to ensure that the footprint indicators as derived from Exiobase are comparable with the control variables used for the three planetary boundaries/four earth system processes defined for this study (cf. Table 2.1). Because of a lack of country-specific data, the footprint indicators do not include Iceland and Liechtenstein. However, the statistical impact of this discrepancy is estimated to be small because of these countries' very low share of the European population (0.06 %). Please refer to Dao et al. (2015) and http://www.bluedot.world for additional information on the methodology.

4.2 Results and critical reflections

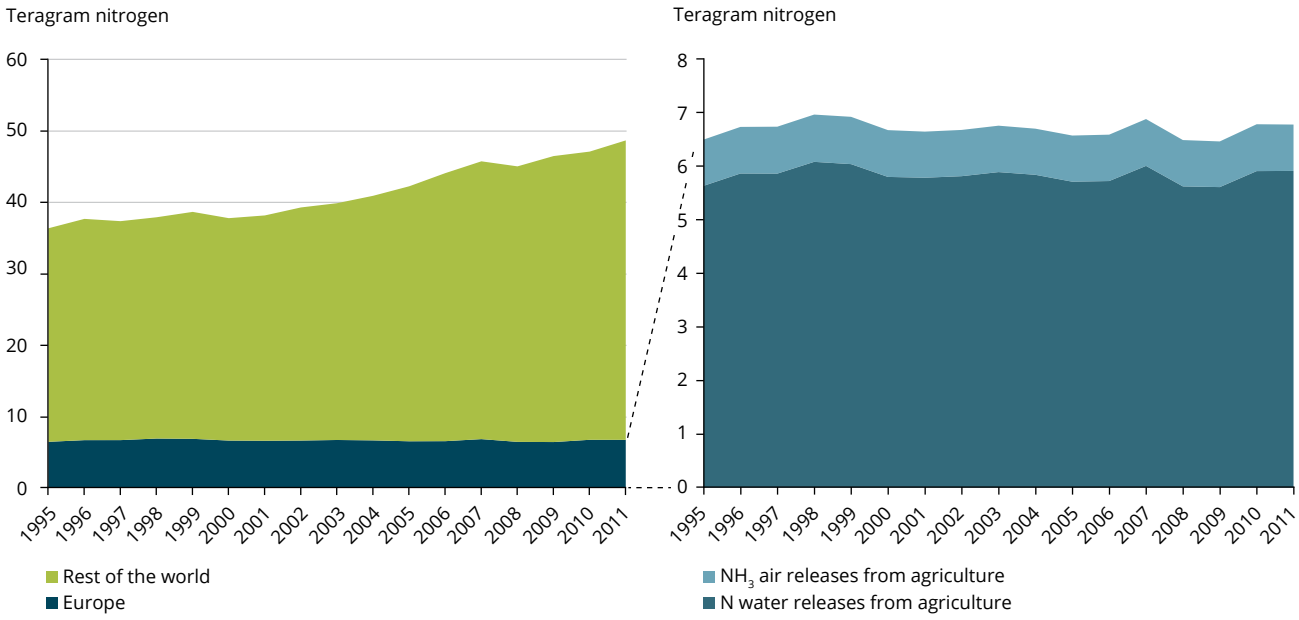
4.2.1 Biogeochemical flows: nitrogen cycle

The nitrogen footprint indicator in this study covers two categories of nitrogen releases included in Exiobase 3.4 — nitrogen from agriculture to water and NH_3 from agriculture to air — so that it is compatible with the definition of the global control variable (cf. Table 2.1). Characterisation factors for converting NH_3 releases to air into losses to water are taken from ReCiPe 2016 — a methodology for life cycle impact assessment (Huijbregts et al., 2016).

Over the period 1995-2011, the yearly global nitrogen losses to water increased by a third (33.9 %). In contrast, the yearly European nitrogen losses to water increased only slightly during that period (by 4.3 %). Thus, the share of the European footprint in yearly global nitrogen losses to water has been decreasing over time, from 18.1 % in 1998 to 13.7 % in 2011 (Figure 4.2, left panel).

For Europe, nitrogen releases from agriculture to water contribute most to the nitrogen footprint (between 86.7 % and 87.3 % in the period 1995-2011). The remaining releases are accounted for by releases of NH_3 from agriculture to air. In 2011, the European footprint amounted to a yearly loss of nitrogen to water of 6.8 Tg (Figure 4.2, right panel) (5.9 Tg for the 28 EU Member States (EU-28)), which is equivalent to 11.4 kilograms of nitrogen (kg N) per capita. In comparison, the yearly global footprint in 2011 was

Figure 4.2 Yearly global and European losses of nitrogen to water (footprint in Tg N), 1995-2011



Source: Own calculations based on Exiobase 3.4.

49.3 teragrams of nitrogen (Tg N) (7.0 kg N per capita) (Figure 4.2, left panel).

Critical reflection

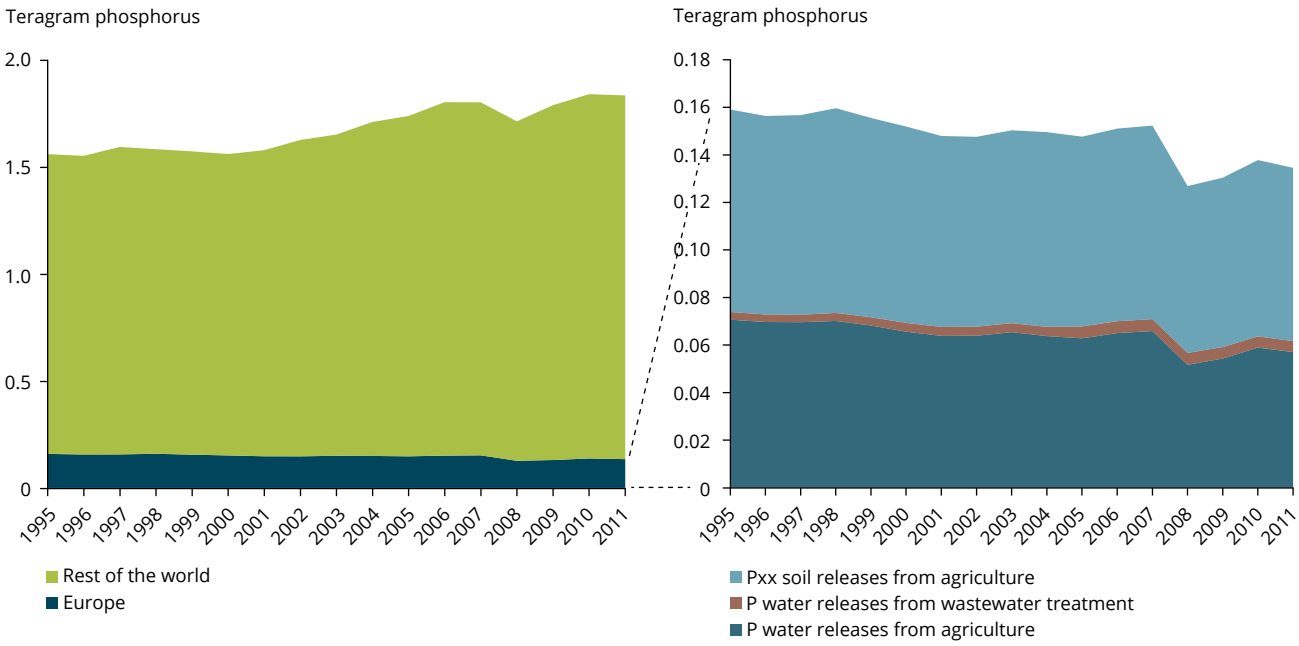
The total global nitrogen footprint computed in this report is smaller than that reported in Dao et al. (2015) (55.6 Tg N), which was taken from the literature (Bouwman et al., 2009) rather than computed using Exiobase. The nitrogen footprints generated with Exiobase are modelled using an approach based on the distribution of fertilisers on crops using specific nutrient requirements that are dependent on production and land use data as well as on the mass balance of nitrogen inputs and outputs (crops and nitrogen emissions) following an Intergovernmental Panel on Climate Change (IPCC) procedure (Merciai and Schmidt, 2016). In a recent study, Exiobase outputs for nitrogen and the related underlying assumptions (e.g. in relation to the allocation of emissions from producing to consuming countries) were used for an assessment of global eutrophication (Hamilton et al., 2018).

Nevertheless, there is not yet final scientific consensus on the magnitude of nitrogen releases from leaching and run-off. This is because of the complexity of modelling the nitrogen cycle and its sensitivity to local behaviours and local soil conditions. Most of the existing computations are based on assumptions and use average values and thus do not include local considerations. Global estimates thus vary considerably. Exiobase includes, for example, nitrogen emissions from leaching and run-off that are 50 % larger than the global model of reference used by Bouwman et al. (2009) (61 compared with 41 million tonnes per year) (Hamilton et al., 2018).

4.2.2 Biogeochemical flows: phosphorus cycle

The phosphorus footprint indicator in this study covers three categories of phosphorus releases included in Exiobase 3.4: phosphorus releases from agriculture to soil, phosphorus releases from agriculture to water and phosphorus releases from waste to water. This is compatible with the definition of the global control variable (cf. Table 2.1). Characterisation factors are taken from ReCiPe 2016 — a methodology for life cycle impact assessment (Huijbregts et al., 2016): a factor of 1 for phosphorus from agriculture to water and from waste to water, and a factor of 0.033 for P compounds (Pxx) from agriculture to soil.

Figure 4.3 Yearly global and European losses of phosphorus to water (footprint in Tg P)



Source: Own calculations based on Exiobase 3.4.

Over the period 1995-2011, yearly global phosphorus losses to water increased by 17.6 %. By contrast, yearly European phosphorus losses to water decreased by 15.4 % during this period. Consequently, the share of the European footprint in yearly global phosphorus losses to water has been decreasing over time: from 10.2 % in 1998 to 7.3 % in 2011 (Figure 4.3, left panel).

For Europe, releases phosphorus compounds from soil to water contribute most to the phosphorus footprint (54.2 % in 2011), followed by direct releases from agriculture to water (42.4 % in 2011) and releases from waste to water (3.4 % in 2011). In 2011, the European phosphorus footprint amounted to a yearly loss of phosphorus of 0.13 Tg (Figure 4.3, right panel) (0.11 for the EU-28), which is equivalent to 0.23 kilograms of phosphorus (kg P) per capita. In comparison, the yearly global footprint in 2011 was 1.8 teragrams of phosphorus (Tg P) (0.26 kg P per capita) (Figure 4.3, left panel).

Critical reflection

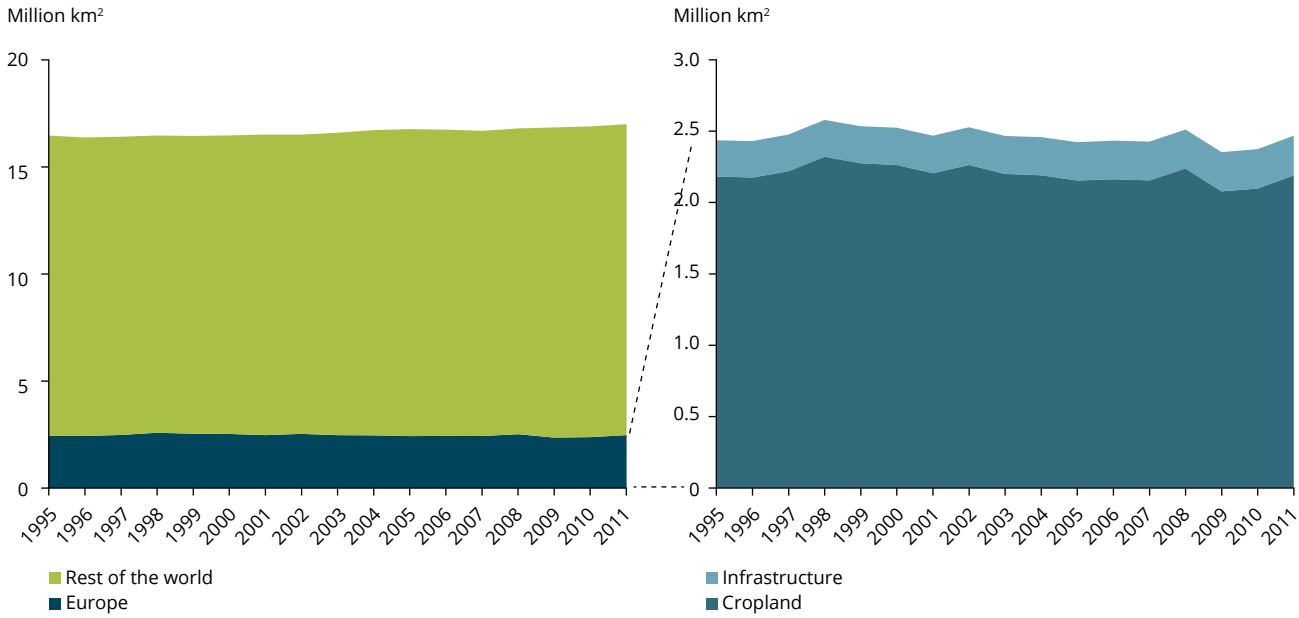
Phosphorus releases are modelled in Exiobase using a similar approach to that used for nitrogen releases (Merciai and Schmidt, 2016). The phosphorus footprints derived from Exiobase were also used in a recent assessment of global eutrophication (Hamilton et al., 2018). There is however a lack of consensus about the size of phosphorus releases from leaching and run-soff. This is because of the complexity of modelling the phosphorus cycle and its sensitivity to local behaviours and local soil conditions. Global estimates thus vary considerably.

Mekonnen and Hoekstra (2011) estimated that the global anthropogenic phosphorus load to freshwater systems (not ocean systems) is 1.5 Tg/year. This value is in the same order of magnitude as the footprint computed in this report. It should be noted that, although phosphorus run-off from agriculture is 10 times larger than from urban waste water, including run-off from urban waste water in the calculation of the phosphorus footprint indicator in this study makes the indicator substantially more comparable with the total footprint considered in Steffen et al. (2015).

4.2.3 Land system change

The land footprint indicator in this study covers two land cover categories included in Exiobase 3.4: cropland

Figure 4.4 Yearly global and European surface area of anthropised land (footprint in million km²)



Source: Own calculations based on Exiobase 3.4.

and infrastructure land, the latter corresponding to urbanised/sealed land. The indicator is therefore compatible with the definition of the global control variable (cf. Table 2.1).

Over the period 1995-2011, the yearly global surface area of anthropised land increased slightly (3.2 %). The yearly European surface area of anthropised land increased marginally (by 1.3 %) over this period. In 2011, it was 4.3 % lower than at its peak in 1998. Overall, the share of the European footprint in the global anthropised surface are did not change substantially between 1995 and 2011, with values ranging between 14 % and 15.7 % (14.5 % in 2011) (Figure 4.4, left panel).

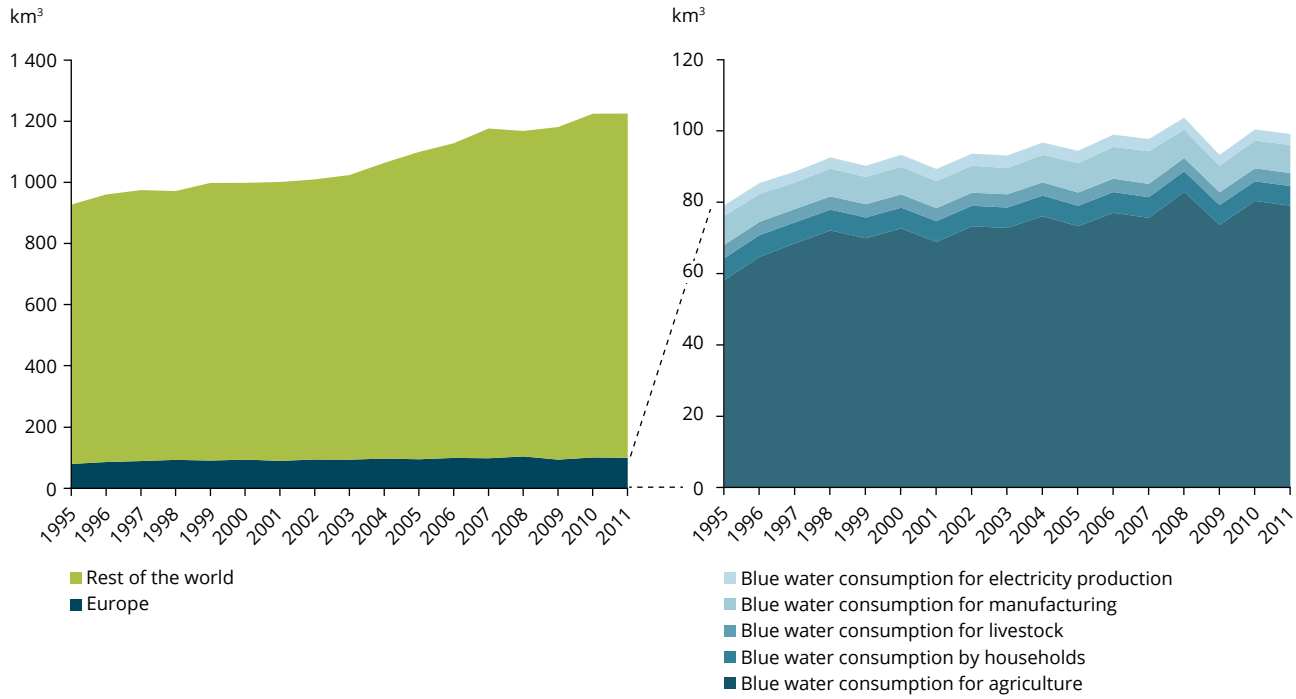
For Europe, cropland contributes most to the European land footprint (88.7 % in 2011), the rest being accounted for by infrastructure land. Cropland is used for economic activities while all infrastructure land is allocated to households (by definition in Exiobase), i.e. it is not allocated internationally through trade. In 2011, the European land footprint amounted to a yearly surface area of 2.5 million km² of anthropised land (Figure 4.4, right panel) (2 million km² for the EU-28), which is equivalent to 4 150 m² per capita. In comparison, the yearly global land footprint in 2011 was around 17 million km² (2 413 m² per capita) (Figure 4.4, left panel).

Critical reflection

In Exiobase, land use data are modelled based on reference data from the Food and Agriculture Organization of the United Nations (FAO) database and on additional assumptions related to the allocation of emissions from producing to consuming countries (Theurl et al., 2018). The results from Exiobase in terms of changes in global and European footprints over time from 1995 to 2008 are very similar to those determined in a study using a different MRIO model (the world input-output database (WIOD)) (Arto Olaizola et al., 2012). The absolute values are however different, being higher in this study than in the WIOD study, both for Europe (26.8 % higher) and for the world (9 % higher).

It should be noted that the modelling of infrastructure land in Exiobase is associated with uncertainties due to limitations in the global data sets used as inputs to Exiobase. While infrastructure land covers less than 5 % of global land, this value is much higher for densely populated countries and thus adds significant uncertainty. The land footprint indicator in this report does not consider permanent pastures, as information

Figure 4.5 Yearly global and European blue water consumption (footprint in km³)



Source: Own calculations based on Exiobase 3.4.

about their relationship with human disturbance ('anthropisation') is not available from the global data set used.

4.2.4 Freshwater use

The water footprint indicator in this study covers five categories of blue water consumption from Exiobase 3.4: agriculture, livestock, manufacturing, electricity towers and electricity once-through. As such, the calculation is compatible with the definition of the global control variable (cf. Table 2.1).

Over the period 1995-2011, yearly global blue water consumption increased by a third (32.1 %). Yearly European blue water consumption increased by 25.3 % during that time. In 2011, it was 4.4 % lower than its peak in 2008. The European share of global blue water consumption did not change substantially between 1995 and 2011, with values ranging from 7.9 % to 9.5 % (8.1 % in 2011) (Figure 4.5, left panel).

The main drivers of the European water footprint are economic activities, with agriculture as the prime contributor (increasing from 73.6 % to 80 % over the period 1995-2011), followed by manufacturing (7.6 % to 10.3 %), livestock (3.6 % to 4.7 %) and electricity production (3.1 % to 3.8 %). Households also contribute to the European water footprint, with the contribution ranging from 5.5 % to 7.7 % over the same period. In 2011, the European water footprint amounted to a yearly blue water consumption of 99.1 km³ (Figure 4.5, right panel) (75.8 km³ for the EU-28), which is equivalent to 166.6 m³ per capita. In comparison, the yearly global water footprint in 2011 amounted to around 1 225 km³ (174 m³ per capita) (Figure 4.5, left panel).

Critical reflection

As accounting data on water withdrawal and consumption are not available for all countries, Exiobase uses modelled data for gap filling, from two main sources: the Water Footprint data set (Mekonnen and Hoekstra, 2011) for agricultural water consumption based on FAO data and the WaterGAP model (Flörke et al., 2013) for industrial water use and water consumption. Both are internationally established sources. Data have been up- and downscaled to cover the range of years of the database, and additional assumptions have been made to allocate data to Exiobase sectors.

5 European and global performances: are footprints within the limits?

This chapter presents the detailed results of analysing the European and global performances for each of the three planetary boundaries/four Earth system processes. In this context, performance refers to the comparison of limits with footprints. The European limits are taken from Section 3.4 (Table 3.4), while the footprint values are taken from Section 4.2. The comparison is performed using the median value across all five allocation principles (which is 7.3 %), but also individually for each allocation principle, for the year 2011.

5.1 Biogeochemical flows: nitrogen cycle

5.1.1 Key messages

- The European limit for nitrogen losses has been overshot.
- This conclusion is valid regardless of the allocation principle.
- Based on the median value across all allocation principles, the European limit for nitrogen losses has been exceeded by a factor of 3.3.
- In comparison, the global limit for nitrogen losses has been exceeded by a factor of 1.7.

5.1.2 Analysis of limits and associated footprints

At the global level, the yearly limit in terms of nitrogen losses from agriculture is 28.5 Tg N (4 kilograms of nitrogen (kg N) per capita) (Table 2.1). The yearly global footprint is 49.3 Tg N (7.0 kg N per capita) (Figure 4.2, left panel), which is 1.7 times larger than the limit.

On the European scale, the yearly limit is 2.1 Tg N (3.5 kg N per capita), based on the median value across all five allocation principles (of 7.3 %; see Table 3.3). The European footprint is equivalent to 6.8 Tg N (11.4 kg N per capita) (Figure 4.2, right panel), which is more than three times the limit. The European limit has thus been exceeded by a higher factor than the global limit.

An analysis of the five allocation principles individually shows that the European limit has been overshot for all allocation principles (Figure 5.1). This means that European nitrogen losses from agriculture are above the limit (and therefore not within Europe's share of the global 'safe operating space') regardless of which of the five normative approaches is chosen to scale match the global nitrogen limit to the European scale.

5.2 Biogeochemical flows: phosphorus cycle

5.2.1 Key messages

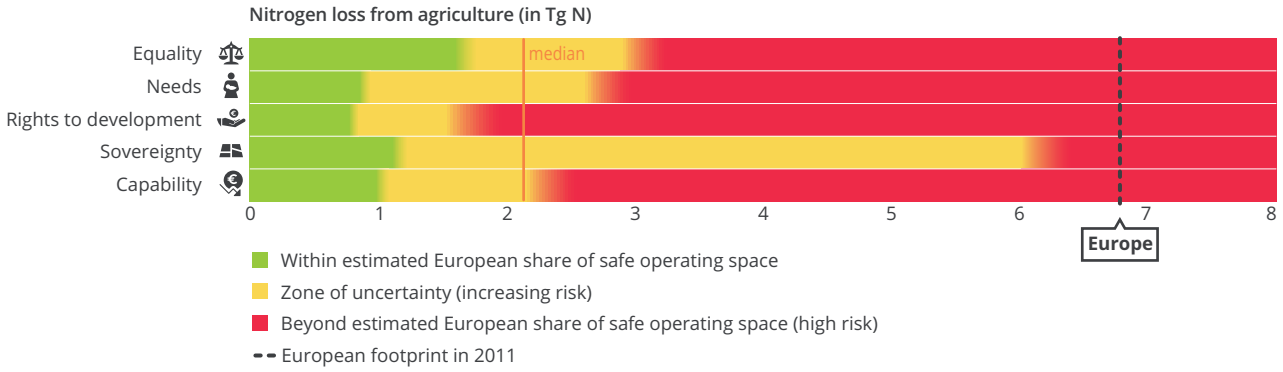
- Despite a decrease in European phosphorus losses to water by around 15 % in the period 1995-2011, the European limit for phosphorus losses has been overshot.
- This conclusion holds for all allocation principles except sovereignty.
- Based on the median value across all allocation principles, the European limit for phosphorus losses has been exceeded by a factor of 2.
- The global limit for phosphorus losses has also been exceeded by a factor of 2.

5.2.2 Analysis of limits and associated footprints

The yearly global limit for phosphorus losses from agriculture and waste is 0.9 teragrams of phosphorus (Tg P) (0.13 kilograms of phosphorus (kg P) per capita) (Table 2.1), while the yearly global footprint is equal to 1.8 Tg P (0.26 kg P per capita) (Figure 4.3, left panel).

On the European scale, the yearly limit is 0.07 Tg (0.11 kg P per capita), based on the median value across all five allocation principles (7.3 %; see Table 3.3). The European footprint is equal to 0.13 Tg P (0.23 kg P per capita) (Figure 4.3, right panel). This means that, both on the global scale and on the European scale, the limits have been overshot by a factor of about 2.

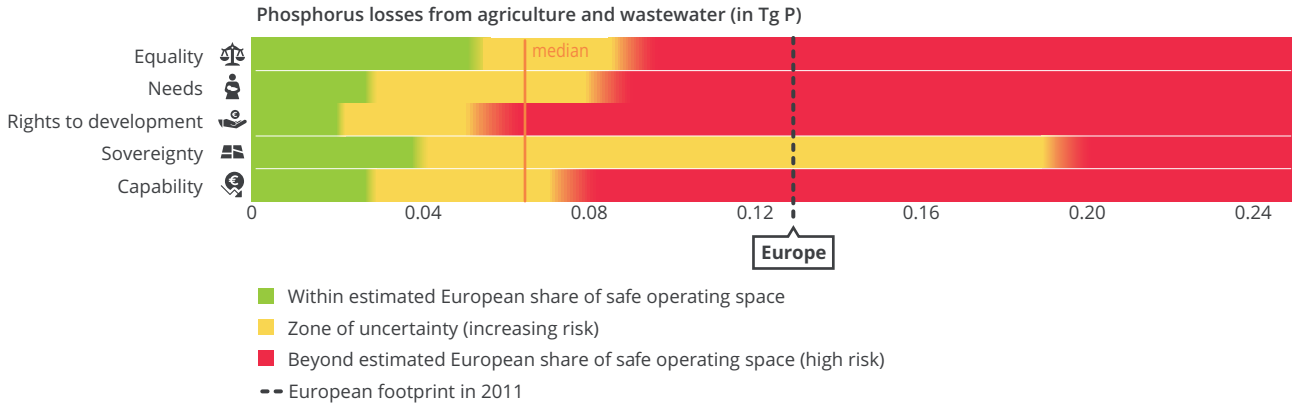
Figure 5.1 European performance for nitrogen losses (in Tg N), 2011



Note: The yellow zone of uncertainty represents the range between the minimum European share and the maximum European share, for each allocation principle (see percentage values in Table 3.3).

Source: Own calculations.

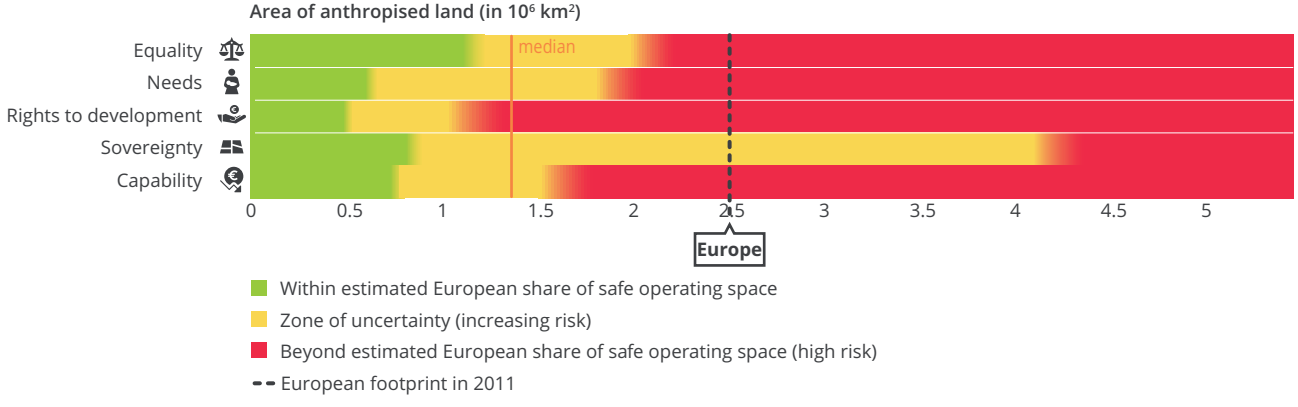
Figure 5.2 European performance (2011) for phosphorus losses (in Tg P)



Note: The yellow zone of uncertainty represents the range between the minimum European share and the maximum European share, for each allocation principle (see percentage values in Table 3.3).

Source: Own calculations.

Figure 5.3 European performance for land cover anthropisation (in million km²), 2011



Note: The yellow zone of uncertainty represents the range between the minimum European share and the maximum European share, for each allocation principle (see percentage values in Table 3.3).

Source: Own calculations.

An analysis of the five allocation principles individually shows that the European limit has been overshot for all allocation principles except sovereignty, i.e. an allocation principle with a strong emphasis on economic needs. For the sovereignty principle, the European limit is within the zone of uncertainty (Figure 5.2)

5.3 Land system change

5.3.1 Key messages

- The European limit for land cover anthropisation has been overshot.
- This conclusion holds for all allocation principles except sovereignty.
- Based on the median value across all allocation principles, the European limit for land cover anthropisation losses has been exceeded by a factor of 1.8.
- The global limit for land cover anthropisation has not been overshot.

5.3.2 Analysis of European limits and associated footprints

The yearly global limit for land cover anthropisation is 19.4 million km^2 (Table 2.1), while the yearly global footprint is equal to 17 million km^2 (2 413 m^2 per capita) (based on data for 2011) (Figure 4.4, left panel). This means that the global footprint has not exceeded the global limit.

On the European scale, the yearly limit is 1.4 million km^2 (2 364 m^2 per capita), based on the median value across all five allocations principles (7.3 %; see Table 3.3). The European footprint is equivalent to 2.5 million km^2 (4 150 m^2 per capita) (Figure 4.4, right panel), which is 1.8 times larger than the limit (based on data for 2011). This means that Europe has overshot its limit in contrast to the situation at the global level where the footprint is below the limit.

An analysis of the five allocation principles individually shows that the European limit has been overshot for all allocation principles except sovereignty (Figure 5.3), as is the case for phosphorus (Section 5.2).

5.4 Freshwater use

5.4.1 Key messages

- Despite an increase in European blue water consumption by around 25 % in the period 1995-2011, the European limit for freshwater use has not been overshot.
- This finding holds regardless of the allocation principle used, but does not preclude the potential local overconsumption of freshwater at the basin level and issues with water scarcity in southern Europe.
- Based on the median value across all allocation principles, the European water footprint is below the European limit by a factor of 3.
- The global water footprint is below the global limit by a factor of 3.3.

5.4.2 Analysis of European limits and associated footprints

The yearly global limit is 4 000 km^3, i.e. 568 m^3 per capita (Table 2.1). The global footprint is equal to 1 225 km^3 (174 m^3 per capita) (Figure 4.5, left panel), which means the global limit has not been overshot.

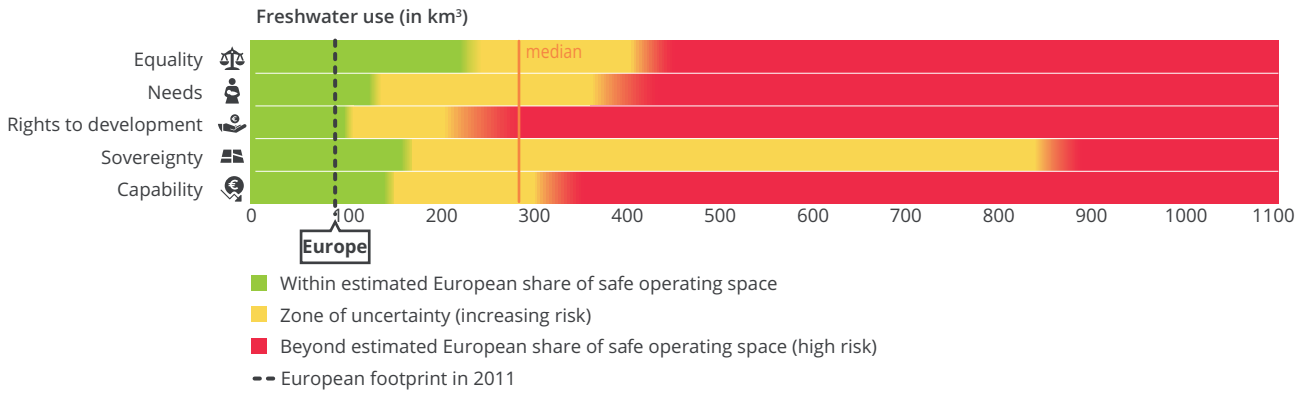
On the European scale, the yearly limit is 291 km^3 (488 m^3 per capita), based om the median value across all five allocations principles (7.3 %; see Table 3.3). The European footprint is equivalent to 99.1 km^3 (166.6 m^3 per capita) (based on data for 2011) (Figure 4.5, right panel). The European situation is thus very similar to the global situation (the footprint being around three times under the limit).

An analysis of the five allocation principles individually shows that the European limit has not been overshot for any of the five normative allocation principles (Figure 5.4).

5.5 Summary of European performance

The comparison of European limits with European footprints based on the median value (7.3 %) across all five allocation principles reveals transgressions for

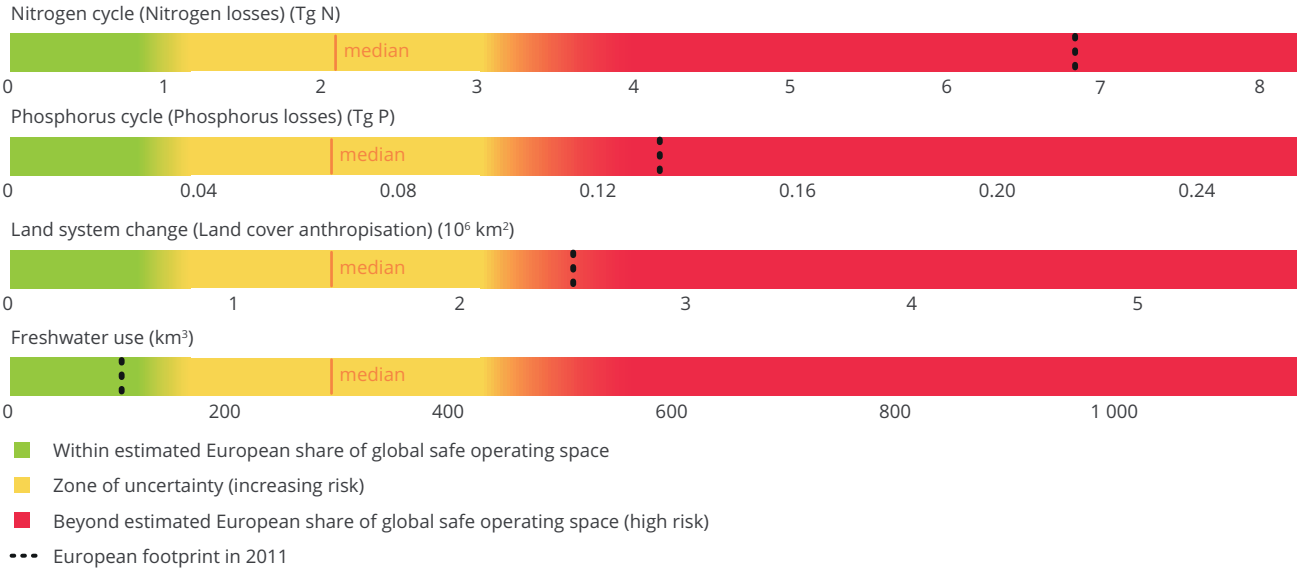
Figure 5.4 European performance for freshwater use (in km³), 2011



Note: The yellow zone of uncertainty represents the range between the minimum European share and the maximum European share, for each allocation principle (see percentage values in Table 3.3).

Source: Own calculations.

Figure 5.5 Overview of European performance, 2011



Note: The yellow range of the figure represents the average range across the five allocation principles, with a median of 7.3 %. This yellow range is defined as the 'zone of uncertainty' to reflect the normative process of defining a European 'safe operating space'.

Source: Own calculations.

three Earth system processes: for both biogeochemical flows — the nitrogen cycle, which shows the highest transgression (by a factor of 3.3), followed by the phosphorus cycle (factor of 2.0) — and for land system change (limit exceeded by a factor of 1.8).

Table 5.1 European limits versus footprints (absolute values), 2011

Planetary boundary		European limit				
Name	**Control variable**	**Minimum**	**Median**	**Maximum**	**European footprint**	**Factor over-/ undershot**
Biogeochemical flows: nitrogen cycle	Loss of nitrogen from agriculture per year (Tg N/year)	0.80	**2.10**	6.00	**6.80**	**3.3**
Biogeochemical flows: phosphorus cycle	Loss of phosphorus from fertilisers and waste per year (Tg P/year)	0.03	**0.07**	0.19	**0.13**	**2.0**
Land system change	Anthropised land (10^6 km^2)	0.50	**1.40**	4.10	**2.5**	**1.8**
Freshwater use	Blue water consumption (km^3)	110	**291**	840	**99.1**	**0.3**

European freshwater use has not been overshot (Figure 5.5 and Tables 5.1 and 5.2).

5.6 Robustness of overall European results

The earlier sections have indicated some of the inherent methodological uncertainties involved in the analysis, e.g. in relation to estimating global limits and computing European footprints. This section briefly evaluates the robustness of the overall findings.

5.6.1 Overall findings in comparison with other studies

Generally, the results of this study based on a consistent footprint methodology (through use of Exiobase 3.4) support the findings from a previous study by Häyhä (2018), which undertook a comprehensive stocktake of the current scientific knowledge base in relation to the European limits for planetary boundaries and the actual European performance. Both studies conclude that Europe has overshot its nitrogen, phosphorus and land system boundaries but not its freshwater boundary. For the freshwater boundary, a Joint Research Centre (JRC) study also came to this conclusion (i.e. that Europe has 'not overshot' this boundary) (Sala et al., 2019). Therefore, despite a range of uncertainties and limitations (see below), the findings on overall European performance (i.e. the magnitude of Europe's over- or undershooting of boundaries; see Section 5.5) are considered fairly robust.

5.6.2 Global limits might change as science improves

The planetary boundaries framework defines nine planetary boundaries. Despite much scientific debate, these nine key Earth system processes have remained largely unchanged since they were first introduced 11 years ago by Rockström et al. (2009), with only slight changes by Steffen et al. (2015). However, the scientific understanding of global environmental limits in relation to planetary boundaries is still evolving. Global environmental limits have not yet been defined for some boundaries, and for other planetary boundaries the limits suggested reflect current scientific understanding and therefore are expected to evolve further as scientific understanding improves. In the case of climate change, which has arguably received most attention through decades of work, e.g. in the context of the Intergovernmental Panel on Climate Change (IPCC), continuous improvement in the understanding of the issue can be noticed. Several authors have operationalised the climate change boundary by focusing on the 2 °C limit, such as Dao et al. (2018). A recent IPCC report on global warming (IPCC, 2018) shows, however, that global the implications of global warming by 2 °C are significantly worse than those of global warming by 1.5 °C . Thus, climate change is an example of an area in which evolving scientific knowledge has led to a re-consideration of the originally proposed global environmental limit. The IPCC report on a 1.5 °C global warming level suggests that the 2 °C limit is not sufficiently precautionary.

5.6.3 Regional context of global limits

Steffen et al. (2015) proposed complementing the global limits with sub-global limits for five planetary boundaries: functional diversity (as part of biosphere integrity), phosphorus (as part of biogeochemical flows), land system change, freshwater use and atmospheric aerosol loading. The objective of introducing sub-global limits is to enable the better representation of the fact that overshooting sub-global boundaries can contribute negatively to the aggregated outcome at planetary level. This means that some

Table 5.2 European limits versus footprints (per capita), 2011

Planetary boundary		European limit				
Name	**Control variable**	**Minimum**	**Median**	**Maximum**	**European footprint**	**Factor over-/ undershot**
Biogeochemical flows: nitrogen cycle	Loss of nitrogen from agriculture per year (kg N/year)	1.3	**3.5**	10.1	**11.4**	**3.3**
Biogeochemical flows: phosphorus cycle	Loss of phosphorus from fertilisers and waste per year (kg P/year)	0.04	**0.11**	0.32	**0.23**	**2.0**
Land system change	Anthropised land (m^2)	894	**2 364**	6 832	**4 150**	**1.8**
Freshwater use	Blue water consumption in (m^3)	185	**488**	1 411	**167**	**0.3**

planetary boundaries can be considered to comprise local/regional processes for which the transgression of sub-global boundaries could accumulate to produce planetary-level impacts. However, only the aggregated global outcome is, by definition, the primary focus of the planetary boundaries framework. Steffen et al. (2015) clearly state that 'The PB [planetary boundaries] framework is therefore meant to complement, not replace or supersede, efforts to address local and regional environmental issues'.

Of the five planetary boundaries with sub-global limits proposed by Steffen et al. (2015), three are considered in this report: biogeochemical flows (phosphorus and nitrogen), land system change and freshwater use. For biogeochemical flows (phosphorus), the reasoning behind the global limit relates to preventing a large-scale anoxic ocean event, while the rationale for the regional limit relates to preventing the widespread eutrophication of freshwater systems. According to Steffen et al. (2015), the current global transgression of the boundary (with a global footprint of 14.2 Tg P/year and a limit set at only 6.2 Tg P/year) results from 'a few agricultural regions of very high P application rates'. These regions are mainly in the United States, Europe, the north of India and China. Indeed, the results of this report show that Europe has exceeded the boundary by a factor of 2. However, there is much variation within Europe (in terms of both sensitivity to P and loss of P to the environment), which is not taken into account in this study.

Similarly, according to Steffen et al. (2015), a few agricultural regions, including those in Europe, with a very high rate of nitrogen application are the main contributors to the global overshooting of this boundary. Indeed, this report concludes that overall Europe has overshot the nitrogen boundary by a factor of 3.3, but it is important to note that, for nitrogen loss, as for phosphorus, the regional context is very important. There are large differences in the nitrogen surplus across Europe (EEA, 2018a; Sutton, 2011), and the sensitivity of the receiving ecosystems also varies. Thus, the scale matching of the phosphorus and nitrogen boundaries to Europe should in principle be made spatially explicit to account for local contexts and effects. However, this goes beyond the scope of this report and could be the focus of a follow-up project.

For freshwater use, Steffen et al. (2015) also considered a control variable at the basin level in terms of blue water withdrawal as a percentage of mean monthly river flows. According to Steffen et al. (2015), the main areas beyond the zone of uncertainty (high risk) are on the west coast of North and Central America, on the coast of North Africa and within a band running from the south of Europe to India and the north of China. While Europe overall is still within its allocated share of water use, there are substantial regional differences within Europe in terms of water availability, with water scarcity problems in some areas especially in southern Europe (EEA, 2018c). The severity of water scarcity and the frequency and severity of drought events are expected to increase in the coming decades, in southern Europe and other parts of Europe, as a result of climate change (EEA, 2017a).

For land system change, Steffen et al. (2015) changed the original control variable of the amount of cropland to the amount of forest cover remaining. Biome level values have been defined for the three major forest biomes — tropical, temperate and boreal — as they play stronger roles in land surface-climate coupling than other biomes. Similarly, the area of anthropised land control variable used in this study also has a regional component, as the impact on the Earth system would depend on where the conversion from natural land to anthropised land takes place.

Overall, there are several reasons why follow-up work on the regionalisation of scale matching would be useful. First, it would help gain a better understanding

of how regional transgressions of limits can contribute to global overshooting. Second, it would help to improve the quality of assessments dealing with global environmental phenomena with an impact on a regional scale, to provide region-specific knowledge that can enable action.

5.6.4 Calculating European shares

This report describes a systematic exploration of allocation approaches with respect to the planetary boundaries framework, from both a theoretical and a quantitative perspective. The range of European shares computed is very wide (from 2.7 % to 21 %), which reflects the very different normative choices involved in such an exercise. For example, assuming European leverage to exert environmental pressures because of its role as major global economic player (as reflected in the allocation principle 'sovereignty') results in the allocation of a much higher share to Europe than if the allocation is based on assuming a more prominent role for developing regions so that they can catch up with developed economies (as reflected in the 'right to development' principle). Only one previous study has used a basket of allocation principles to define sub-global shares of planetary boundaries (Lucas and Wilting, 2018).

Nonetheless, the explorations could be made even more comprehensive and systematic. Additional computation methods could have been considered, as well as more recent years. The results of this study cover only a period up to 2011, as the most recent version of Exiobase (version 3.4 released in 2018) includes reported data for only the years 1995-2011. However, initial explorations towards extending the time period up to a more recent year (2017/2018) indicate that additional years would most likely not significantly change the overall results. Therefore, despite being from 2011, the results are considered robust enough to gain an understanding of the magnitude of European planetary boundary transgressions. While there are other multiregional input-output (MRIO) models (e.g. EORA, WIOD, GTAP and FABIO models), Exiobase was deemed the most suitable for this analysis given its range of environmental extensions and level of disaggregation. Furthermore, it is considered very robust and is funded by the European Commission (through the Desire project — a Seventh Framework Programme — FP7 — research project).

5.6.5 Uncertainty in relation to European footprints

European footprints can be calculated using different MRIO models. This study used Exiobase 3.4 (Stadler et al., 2018), which was developed as part of the EU project Desire, funded by the European Commission, and has been widely used in other scientific footprint studies (e.g. Wood et al., 2018). Unlike an earlier European-scale study (Häyhä et al., 2018), which reviewed findings across a range of footprint studies based on different MRIO models and calculation approaches, this analysis is based on an internationally harmonised database (Exiobase 3.4). It therefore enables a consistent footprint methodology to be applied across all boundaries assessed. The global footprints obtained using Exiobase yield results that are compatible with previous studies by Dao et al. (2015, 2018) and the blueDot project (http://www.bluedot.world).

While some degree of uncertainty in the footprint results, due to methodological choices on footprint calculations, is expected (see the critical reflections of Sections 4.2.1 to 4.2.4), this variation is judged to be much smaller than the magnitude of the transgressions of the European limits (Section 5.5).

6 Case study for Switzerland: biosphere integrity (genetic diversity)

Steffen et al. (2015) proposed a two-component approach to address two key roles of the biosphere in the Earth system: genetic diversity and functional diversity. The first 'captures the role of genetically unique material as the "information bank" that ultimately determines the potential for life to continue to coevolve with the abiotic component of the Earth system in the most resilient way possible.' As an interim variable, they proposed 'the known global extinction rate of well-studied organisms over the past several million years', which considers the 'long-term capacity of the biosphere to persist under and adapt to abrupt and gradual abiotic change' although 'it is measured inaccurately and with a time lag'. The second 'captures the role of the biosphere in Earth-system functioning through the value, range, distribution, and relative abundance of the functional traits of the organisms present in an ecosystem or biota'. As an interim control variable, they proposed the Biodiversity Intactness Index (BII). Steffen et al. (2015) clearly mentioned that these should be considered interim control variables, applicable only until more appropriate ones are developed.

While some approaches exist to assess the development of ecosystem and species diversity on the global scale, such as the work of the Biodiversity Indicators Partnership (BIP) ([7]), an EU-wide analysis of biosphere integrity has not been conducted for this report. Currently available models and proxy data are not judged to do justice to the complexity of biosphere integrity, its highly local and regional nature, and its interconnectedness with and dependence on other processes. However, new innovative approaches are being developed and could be applied in the future assuming they are proven robust enough for an adequate accounting approach. One example is a recent approach for Switzerland by Frischknecht et al. (2018), which is presented briefly here.

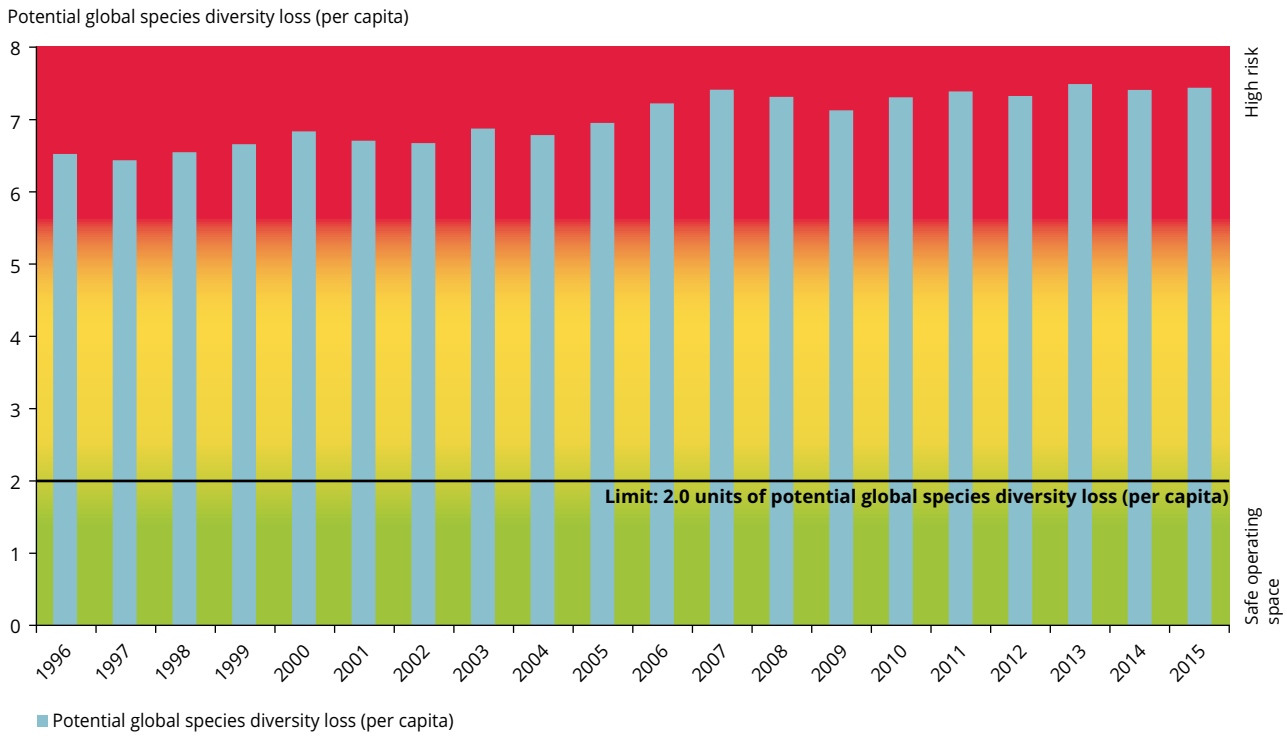
The biodiversity footprint for Switzerland was calculated based on the interim recommendations of the Life Cycle Initiative ([8]), hosted by UN Environment, which is also discussed by Meyer and Newman (2018). This indicator is a further development of a similar indicator implemented in Frischknecht et al. (2018) and Dao et al. (2018), and has recently been updated and extended (Chaudhary and Brooks, 2018).

The biodiversity footprint for Switzerland was calculated as the potential for global species loss due to land use. This indicator quantifies the long-term expected potential loss caused by specific land use types (such as for agriculture or settlements) compared with an untouched, natural reference state. As such, it is a representation of pressures on biodiversity and the associated expected impacts and not a representation of actual *in situ* measurements of biodiversity loss. The indicator takes into account the vulnerability of species and converts the regional decline of widespread species and the global extinction of endemic species into units of 'completely globally extinct species'. The equivalents of potentially globally extinct species are integrated over the years and quantified per million species or per billion species (potential global species diversity loss) ([9]). Using comparisons with a natural state, the indicator describes the likelihood that species will become irreversibly extinct as a result of current land use. The indicator addresses land use as a main driver of biodiversity loss, while other drivers such as eutrophication, climate change, the use of pesticides and habitat fragmentation are not addressed.

To calculate Switzerland's biodiversity footprint, a combination of data sources were used: domestic emissions inventories, trade data and life cycle assessment data. Given that the biodiversity impacts of land use are highly location specific, life cycle assessment data were regionalised on a country scale, based on the World Food Life Cycle Database (WFLDB) (Nemecek et al., 2015) and Pfister et al.(2011).

([7]) https://www.bipindicators.net
([8]) https://www.lifecycleinitiative.org/applying-lca/lcia-cf/
([9]) The units of potential global species diversity loss are 'pico-PDF · a', where pico stands for 10^{-12} and PDF for the potentially disappeared fraction of species 1; pico-PDF · a = 10^{-12} PDF · a (i.e. a trillionth of PDF · a); the term '· a' refers to the integration over time.

Figure 6.1 Development of Switzerland's consumption-based biodiversity footprint per capita



Source: Frischknecht et al. (2018).

Notes: The development of consumption-based pressure on biodiversity due to land use is expressed as 'potential global species diversity loss'. Other factors that influence biodiversity, such as pollutant loads or fragmentation effects, are not taken into account.

Switzerland's biodiversity footprint was compared with the boundary for biosphere integrity proposed by Steffen et al. (2015). As mentioned above, they proposed using the yearly global extinction rate as an interim control variable with a boundary value of ≤ 10 yearly extinctions per million species-years (E/MSY). As a second control variable, Steffen et al. (2015) proposed the BII. The former control variable has been used and operationalised as described below.

The first large-scale human influence on biodiversity was caused by deforestations by humans, which happened in Europe between AD 500 and 800. Since then, i.e. in the last 1 500 years, around 1 500 species per million species have become extinct worldwide naturally, i.e. without human interference. An extinction rate of 10 species per million species and per year over the last 1 500 years, or 15 000 species per million species, was therefore assumed as the threshold value. Applying an equal share per capita approach, a yearly per capita limit for the global loss of species was deduced. This resulted in a value of 2 units of potential global species diversity loss.

The Swiss biodiversity footprint per capita increased from 1996 to 2015 by around 14 % and was 7.5 units of potential global species diversity loss in 2015 (Figure 6.1). In absolute terms, it totalled nearly 62 species-years per million species. The planetary boundary threshold value is 73 % and the natural extinction rate is 97 % below that value. In other words, the Swiss biodiversity footprint exceeds the planetary boundary threshold value by 270 %.

The biodiversity footprint presented here is inevitably a simplification of the complex issue of biosphere integrity. However, it gives a reasonable indication of where in the world the consumption of a country is likely to affect biodiversity most. There is ongoing discussion about the operationalisation of biodiversity in national footprints — see, for example, Mace et al. (2014), Marques et al. (2017) and Crenna et al. (2019). Most recently, the International Resource Panel (IRP) (2019), as well as Cabernard et al. (2019), applied this indicator for global assessments. Chaudhary and Brooks (2019) applied a similar approach to assessing the biodiversity impacts of national consumption and world trade and critically discussed its merits and shortcomings. Chaudhary and Brooks (2018) derived more up-to-date characterisation factors for projecting potential species losses.

7 Implications for policy and knowledge developments

7.1 Policy

In recent years, substantial policy focus on different scales of governance has been dedicated to **climate change** given the Paris Agreement, the comprehensive knowledge base provided by the Intergovernmental Panel on Climate Change (IPCC) and the fact that climate change impacts are becoming ever more visible and real for societies. In parallel, the challenge of global **biodiversity loss/biosphere integrity** has recently gained traction on the policy agenda, driven by the work of the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) and ambitious objectives for the United Nations Convention on Biological Diversity (UNCBD) 15th meeting of the Conference of the Parties (COP 15), to be held in October 2020. These two priorities (i.e. climate change and biodiversity loss) are also very high on the EU policy agenda for the European Green Deal (EC, 2019b).

As much as climate change and biodiversity loss/biosphere integrity are crucial systemic issues in themselves, they are also intimately linked to other Earth system processes. In the planetary boundaries framework, climate change and biosphere integrity are therefore acknowledged as the two core boundaries (Steffen et al., 2015). Because of the interlinkages mentioned, progress towards addressing the issues of climate change and biosphere integrity can be hampered by lack of progress in addressing other planetary boundaries such as **biogeochemical cycles**, **land system change** and **freshwater use**. This analysis highlights (and reconfirms) that Europe would be wise to prioritise these additional key systemic challenges, in particular the nitrogen and phosphorus cycles and land system change.

As implicitly stated in the Seventh Environment Action Programme (7th EAP), there is a need for European policy targets to reflect global environmental limits. Assessments such as this report can potentially inform the setting of policy targets on these issues — by bringing an Earth system perspective and applying principles drawn from climate change negotiations to other environmental issues (Bringezu, 2019; EEA, 2019a).

This report finds that, to stay within the European share of the global safe operating space, the European footprint should be reduced by a **factor of about 3** for nitrogen losses and a **factor of about 2 for phosphorus losses**. In addition, a reduction by almost a **factor of 2** would be needed for **land cover anthropisation**. Europe is not overshooting its share of freshwater use. However, as stated in previous sections, these results derived from a top-down approach disguise existing regional European issues with freshwater use (e.g. the relative abundance of water in northern Europe and scarcity of water in southern Europe, increasingly affected by climate change).

Given the involvement of **normative choices** in defining the allocation approaches, a **public dialogue** both within countries and between countries on how to share burdens, roles and responsibilities in implementing the UN 2030 Agenda for Sustainable Development could be a means to further operationalise these results. In addition, dialogue among experts is needed to discuss quantitative aspects (such as calculation methods) as well as normative (ethical and juristic) aspects of the allocation principles and what they mean for implementation.

This analysis could in turn inform discussions on possible policy targets. These discussions would benefit from first exploring to what extent planetary boundary issues are already covered by existing policies and whether or not implementation of these policies in a more integrated and coherent way would help to address the main issues needed to stay within European boundaries. Below is a short overview of the European policy frameworks for the four issues analysed in this report:

- **Nitrogen cycle:** the 7th EAP calls for further efforts to manage nutrient cycles (N and P cycles) in a more sustainable way and to improve the efficiency of the use of fertilisers. However, there are no EU environmental acquis objectives that match this 7th EAP objective directly (EEA, 2018b), although several EU directives relate to the nitrogen cycle. For example, the EU Nitrates Directive aims to reduce

water pollution by nitrates from agricultural sources and prevent pollution of groundwater and surface water. There are several other EU directives that are relevant to the impact of excessive nutrient use in agriculture, e.g. the EU Water Framework Directive and the National Emission Ceilings (NEC) Directive (EEA, 2018b). However, these directives seek to reduce the territorial nitrogen footprint within the EU and do not deal with the growing external nitrogen footprint caused by European consumption of imported goods, especially agricultural commodities.

- **Phosphorus cycle:** the 7th EAP objective to improve the efficiency of the use of fertilisers is also relevant to the phosphorus cycle. However, similarly to nitrogen, there are no EU environmental acquis objectives that match this 7th EAP objective for phosphorus, although some EU directives relate to the phosphorus cycle such as the Water Framework Directive, the Urban Waste Water Treatment Directive and the Nitrates Directive. The Nitrates Directive has the objective of reducing eutrophication, which in turn is determined by the levels of phosphorous in freshwater. Thus, the designation of nitrate vulnerable zones, in which the use of fertilisers and therefore phosphorus leaching are limited, is an important measure for improving the negative impacts of phosphorus on aquatic ecosystems.

- **Land system change:** the 7th EAP includes an objective that requires land to be managed sustainably and promotes the objective of no net land take by 2050, but there is no specific objective in the EU environmental acquis that matches this 7th EAP objective (EEA, 2018b). The objective of no net land take by 2050 focuses on no net land take in Europe and not by Europe (i.e. a territorial rather than a consumption-based perspective). The lack of a strategic policy framework on land, including binding targets, has been highlighted as a major EU policy gap for catalysing systemic change (EEA, 2019b).

- **Freshwater use:** the 7th EAP aims to ensure that, by 2020, stress on renewable freshwater resources is prevented or significantly reduced in the EU. The EU Water Framework Directive (WFD) objective of achieving 'good' status also requires ensuring that there is no overexploitation of water resources, since the quantity, not only the quality, of freshwater resources is closely linked to achieving good status. Both the 7th EAP objective and the WFD focus on freshwater use within the EU and do not therefore capture issues such as Europe's virtual water footprint.

Overall, existing thematic policies aim to a varying degree to reduce the pressures associated with nitrogen, phosphorus, land and water in Europe. However, recent complementary assessments indicate that these policy efforts are not sufficient. The environmental challenges related to the nutrient cycles (nitrogen and phosphorus cycles), land and water **are not sufficiently addressed in an integrated and systemic way**. For example, tackling diffuse nutrient (nitrogen and phosphorus) pollution will require more coherent policies for agriculture, transport, industry and waste water treatment, while an integrated and overarching policy framework is needed to tackle issues related to land and soils (EEA, 2019b). In addition, there are policy gaps when it comes to the contribution that Europe's external footprint, caused by the consumption of imported goods, makes to Europe's overshooting of its shares in planetary limits (in terms of trade policy, Europe as global leader in sustainability, etc.).

The development of an **8th EAP** provides an opportunity to better operationalise the meaning of '**living well, within the limits of our planet**'. For example, by more comprehensively capturing the systemic nature of todays environmental challenges (i.e. their interlinkages and the need to address them in a more holistic manner), by recognising that European limits can be calculated (i.e. thereby guiding whether or not Europe lives within its environmental limits) and by addressing the environmental pressures that Europe exerts abroad. Assessments such as this report can also help guide the process of implementing the Sustainable Development Goals — at global, European and national levels — in relation to target setting, as well as for the monitoring, reporting and reviewing of their implementation.

While there still is a strong role for thematic polices, especially in relation to existing implementation gaps (EEA, 2019b), there is also increasingly a need to anchor these policies in more systemic policy frameworks that cut across traditional policy domains to address the underlying drivers of unsustainability, which is ultimately the root cause of the overshooting of many of the planetary boundaries (EEA, 2019b). In particular, it is increasingly clear that profound transformations in the **systems of consumption and production,** e.g. in relation to the systems of food, energy and mobility, are needed (EEA, 2015, 2019b; IPCC, 2018; IPBES, 2019; Sala et al., 2019; UN Environment, 2019).

The specific boundaries assessed in this study — the nitrogen and phosphorus cycles, land cover anthropisation and freshwater use — are **particularly strongly driven by the food system**, e.g. nutritional and agricultural patterns. As such, this study reconfirms the findings that environmental pressures associated

with Europe's food system are considerable. Moreover, Europe's food system is strongly interwoven with its societies and economies, cultural values and landscape patterns (EEA, 2017b). Indeed, a recent EAT-Lancet Commission report (Willett et al., 2019) demonstrates that, to feed a future world population of 10 billion people, transforming eating habits, improving food production and reducing food waste will be essential if a global healthy diet is to be achieved within planetary boundaries. Crucially, transforming eating habits is also needed from a nutritional health point of view (Chen et al., 2019). With the EU consumption of animal protein being about twice the global average, there is a particular need to reduce meat consumption. This would lead to reductions in both environmental pressures from Europe's food system and the overall European disease burden (PBL, 2011).

Thus, a key leverage point for staying within the limits of the planetary boundaries assessed in this study is **to transform the food system**. Embracing a wider food system perspective — beyond thematic and sectoral policies — would be particularly beneficial, because diffuse nutrient pollution is also influenced by society's consumption patterns, such as in terms of food choices (EEA, 2019b). There are already growing calls for the EU to develop a 'common food policy' (EESC, 2017; IPES Food, 2018). The ambitions of the European Commission under the European Green Deal for a **'farm to fork strategy'** on sustainable food along the whole value chain (EC, 2019b) provide an opportunity to build a comprehensive policy framework addressing the root causes of exceeding planetary limits.

7.2 Knowledge

The 7th EAP, 'Living well, within the limits of our planet', which guides European environment policy until 2020, explicitly acknowledges the need for further knowledge on planetary boundaries in its priority objective 5: 'To improve the knowledge and evidence base for Union environment policy', which states:

> While available evidence fully warrants precautionary action …, **further research into planetary boundaries**, systemic risks and our society's ability to cope with them will support the development of the most appropriate responses (EC, 2013, p. 60).

As mentioned in the report's preface, this knowledge gap was considered of strategic importance by the Environmental Knowledge Community (EKC), resulting in the knowledge innovation project (KIP) 'within the limits of our planet' (WiLoP), with the aim of developing knowledge for future-oriented strategic policymaking in relation to 'living well, within the limits of our planet'.

This report provides some important advances in our understanding of how the concept of planetary boundaries can be operationalised in Europe by (1) demonstrating how European shares of planetary limits can be calculated for several planetary boundaries, building on lessons learned from the context of climate change negotiations, and (2) linking these shares to consumption-based footprints for Europe derived from a state-of-the-art multiregional input-output (MRIO) database (Exiobase).

Nevertheless, many important knowledge gaps remain, in particular in relation to the following:

- **Understanding global environmental limits:** the planetary boundaries concept defines limits for six of the nine planetary boundaries, but limits still remain to be defined for the other three. This is also part of the reason why the analysis presented in this report was restricted to three planetary boundaries. Even for the planetary boundaries for which limits have been defined, they are associated with significant uncertainty, and the limits must be expected to be continuously revised as scientific knowledge improves. This also relates to better understanding the risk of impacts in terms of what level can be considered safe and what level constitutes a high risk.

- **Global versus regional boundaries:** this report allocated specific values for European shares based on globally defined limits. However, the planetary boundaries differ with respect to their spatial scopes and limits, and while some planetary boundaries can be considered truly global processes (e.g. climate change), others also have a more regional/local character. Indeed, Steffen et al. (2015) proposed complementing the global limits with sub-global limits for five of the planetary boundaries: functional diversity (as part of biosphere integrity), phosphorus (as part of biogeochemical flows), land system change, freshwater use and atmospheric aerosol loading. Thus, there is a need to better understand the relationship between global and regional processes, e.g. through a better integration of the multi-scale dimension of environmental pressures into the concept of environmental boundaries.
- **The need to better understand European environmental footprints:** this report concludes that there is a need to considerably reduce some European footprints to stay within the European shares of planetary boundaries. Despite considerable recent scientific progress in quantifying the environmental footprints embodied in internationally traded products through approaches such as MRIO databases, there is still much scope to improve the understanding of footprint data, accounts and indicators. This relates particularly to the application of these approaches to additional environmental themes such as biodiversity, but also to making them more spatially explicit to better capture where impacts are happening. To make this happen, financial investments into updating (with more recent years) and further developing footprinting approaches will be needed.

Abbreviations

7th EAP	Seventh Environment Action Programme
BII	Biodiversity Intactness Index
CERP	Climate Equity Reference Project
CFC	Chlorofluorocarbon
DG	Directorate-General
EEIO	Environmentally extended input-output
EKC	Environmental Knowledge Community
EU-28	28 EU Member States
FAO	Food and Agriculture Organization of the United Nations
FOEN	Swiss Federal Office for the Environment
FP7	Seventh Framework Programme
GDP	Gross domestic product
GHG	Greenhouse gas
HDI	Human Development Index
IEA	International Energy Agency
IPBES	Intergovernmental Platform for Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRIO	Inter-regional input-output
IRP	International Resource Panel
JRC	Joint Research Centre
kg N	Kilograms of nitrogen
kg P	Kilograms of phosphorus
KIP	Knowledge innovation project
MRIO	Multiregional input-output

Mt N	Megatonnes of nitrogen
NO_x	Nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
PBL	Netherlands Environment Assessment Agency
PPP	Purchasing power parity
SDG	Sustainable Development Goal
Tg N	Teragrams of nitrogen
Tg P	Teragrams of phosphorus
TRAIL	Trade and life cycle assessment
UNCBD	United Nations Convention on Biological Diversity
UNFCCC	United Nations Framework Convention on Climate Change
WFD	Water Framework Directive
WFLDB	World Food Life Cycle Database
WiLoP	Within the limits of our planet

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Annex 1 Computation methods used for each allocation principle

Some of the scenarios presented apply transformation functions based on logs or saturation points. In both cases, the objective is to attenuate the importance of large values. When information is available for setting thresholds, linear relationships have been complemented with saturation points (computation methods 7 and 12). When information on thresholds is lacking, values have been transformed using logs (computation methods 4, 6 and 10).

All data for computing the minimum, average, median and maximum European share values are for 2011 except in the case of computation method 8 — land (2010 data) — and computation method 9 — biocapacity (2013 data).

Allocation principle A: equality

Computation method 1: equal share per capita

All inhabitants of the planet are assumed to have the same right to use its resources in a specific year. The allocation to countries is based on the country share of the world population in that year. Three scenarios are built by varying the year considered (1990, 2000 or 2011).

- Allocation key: total population, both sexes combined.
- Unit: persons.
- Source: UN Population Division, World Population Prospects 2017 (https://esa.un.org/unpd/wpp/).
- Scenarios: three scenarios are built by varying the year considered — 1990, 2000 or 2011.
- Function: the European share is equal to the European population divided by the world population.

Computation method 2: equal share per capita over time

All inhabitants of the planet over a given period of time are assumed to have the same yearly right to use the resources. The allocation to countries is based on the country share of the world cumulative population over time. Six scenarios are built to consider various cumulative populations by varying the start year (1990, 2000 or 2011) and the end year (2050 or 2100).

- Allocation key: total population, both sexes combined (cumulated), medium fertility variant for years 2050 and 2100.
- Unit: persons.
- Source: UN Population Division, World Population Prospects 2017 (https://esa.un.org/unpd/wpp/).
- Scenarios: six scenarios are built by varying the start year (1990, 2000 or 2011) and end year (2050 or 2100).
- Function: the European share is equal, for a given period, to the sum of the yearly European population during this period divided by the sum of the yearly world population during the same period.

Allocation principle B: needs

Computation method 3: equivalence between children and adults

The Organisation for Economic Co-operation and Development (OECD) equivalence scale is based on the principle that a child only needs 30 % of the financial resources needed by an adult. The same logic is applied here: the allocation to countries is based on the share of the world population weighted by an equivalence scale (people aged 0-14 are weighted 0.3, others are weighted 1). A single scenario is considered for the year 2011.

- Allocation key: population, share of ages 0-14 years, OECD equivalence scale.
- Unit: percentage of total.
- Source: OECD equivalence scales (http://www.oecd.org/eco/growth/OECD-Note-EquivalenceScales.pdf).
- Function: the European share is equal to the European population weighted by age (weight = 0.3 for the share of the population aged 0-14 and 1 for the rest of the population) divided by the world population weighted by age (as for the European population).

Computation method 4: accessibility

Accessibility is considered the potential for interactions and for reaching opportunities to fulfil personal needs. The quantification of accessibility is based on the accessibility map 'Travel time to major cities'. The metric used measures the 'travel time to a location of interest using land (road/off road) or water (navigable river, lake and ocean) based travel'. The accessibility map is combined with a population map to obtain a national indicator of the weighted average of travel time per capita. The indicator is expressed in minutes per capita. The higher the value of the indicator, the higher the average travel time to city centres, hence the higher the allowance of resources. The allocation to countries is based on the share of the world population weighted by the indicator value. Two scenarios (based on raw values and logarithmic values) are considered for the year 2011.

- Allocation key: travel time to major cities.
- Unit: minutes per capita.
- Source: own calculations based on the data set 'Travel time to major cities: a global map of Accessibility' accessible from the Joint Research Centre (JRC) web page http://forobs.jrc.ec.europa.eu/products/gam/ (Uchida and Nelson, 2008).
- Scenarios: scenario 1 — no transformation; scenario 2 — logarithm transformation of minutes per capita.
- Function: the European share is equal to the European population weighted by the average per capita travel time (computed from raster maps of accessibility and population at 1-km spatial resolution) divided by the world population weighted by the average per capita travel time (as for the European population).

Computation method 5: nutrition

The quantification of nutrition is based on the multidimensional metric 'Food Nutrient Adequacy', which is the average score (on a normalised scale of 0-100) of six nutrition indicators (Shannon Diversity of Food Supply, Non-Staple Food Energy, Modified Functional Attribute Diversity, Population Share with Adequate Nutrients, Nutrient Balance Score and Disqualifying Nutrient Score). The higher the metric, the more adequate the nutrition. The allocation to countries is based on the share of the world population weighted by the distance to the theoretical maximum score of 100. The higher the distance, the higher the allocation. A single scenario is considered for the year 2011.

- Allocation key: the Food Nutrient Adequacy metric.
- Unit: score on a scale of 0-100.
- Source: Chaudhary et al. (2018) ([10]).
- Function: the European share is equal to the European population weighted by the distance to the theoretical maximum Food Nutrient Adequacy score of 100, divided by the world population weighted by the distance to the theoretical maximum Food Nutrient Adequacy score of 100 (as for the European population).

Allocation principle C: right to development

Computation method 6: poverty line

The application of the right to development principle is based on the idea that people earning less than a minimum daily income can continue to emit as much as they need to allow for development, and that, above this threshold, people have to converge to a commonly shared equilibrium level over the years. This idea is adapted here to match the concept of a budget rather than a reduction target. The allocation to countries is based on the share of people earning up to USD 5.50 a day, i.e. the poverty line for upper-middle countries by the World Bank. One scenario has been built, which

([10]) The data is found in the supplementary data of Chaudhary et al. (2018)

considers an allocation to countries based on their share of the world population earning up to USD 5.50 a day in the year 2011. To reduce in impact of extreme values, lower and upper boundaries (corresponding to the minimum (0.1 %) and maximum (95 %) values observed in the countries data set) are set and a log scale is adopted.

- Allocation key: poverty headcount ratio at USD 5.50 a day (2011 purchasing power parity (PPP)).
- Unit: percentage of population.
- Data source: World Bank, World Development Indicators (https://data.worldbank.org/indicator/SI.POV.UMIC).
- Function: the European share is equal to the European population weighted by the percentage of people at USD 5.50 a day (2011 PPP) divided by the world population weighted by the percentage of people at USD 5.50 a day (2011 PPP) (as for the European population).

Computation method 7: development level

The Human Development Index (HDI) is a composite index of life expectancy, education and per capita income. The allocation to countries is based on the share of the world population weighted by the national HDI. Two scenarios are considered for the year 2011. The first weights countries using the distance to the maximum HDI level (= 1); for example, for Europe, the weight is equal to 0.14 (1 - 0.86), while it is equal to 0.34 for the rest of the world. The second scenario applies minimum and maximum caps (at 0.55 and 0.8 corresponding to limits of 'low' and 'very high' HDI categories): below an HDI equal to 0.55, the right to resources is equivalent to the country share of the world population; between 0.55 and 0.8, the share declines linearly; and above an HDI of 0.8, there is a weighting equal to 0.2 (to allow for the minimum use of resources in each country). The 0.2 weighting means that Europe is favoured in this second scenario compared with the first scenario.

- Allocation key: HDI.
- Unit: unitless.
- Source: United Nations Development Programme, Human Development Reports, Human Development Index (http://hdr.undp.org/en/indicators/137506).
- Scenarios:
  - Scenario 1: distance to the theoretical maximum HDI level (= 1); Europe = 1 - 0.86 = 0.14, rest of the world = 1 - 0.66 = 0.34;
  - Scenario 2: saturation points set at 0.55 and 0.8 (corresponding to limits of 'low' and 'very high' HDI categories).
- Function: the European share is equal to the European population weighted by an inverse function of the HDI divided by the world population weighted by an inverse function of the HDI (as for the European population).

Allocation principle D: sovereignty

Computation method 8: land

Countries are allowed to use natural resources in proportion to their geographical size (land area). The allocation to countries is based on the country share of the world land area at a specific date. A single scenario is considered for the year 2010.

- Allocation key: land area.
- Unit: ha.
- Source: Food and Agriculture Organization of the United Nations (FAO), 'Land Use' data (http://www.fao.org/faostat/en/#data/RL).
- Function: the European share is equal to the European land area divided by the world land area.

Computation method 9: biocapacity

Countries are allowed to use their own natural resources. The allocation to countries is based on the country territorial share of the world resources (approximated as the biocapacity computed by the Ecological Footprint Network) at a specific date. A single scenario is considered for the year 2013.

- Allocation key: biocapacity.
- Unit: global hectares (gha) per person.
- Source: Global Footprint Network, 2017 Edition National Footprint Accounts: ecological footprint

and biocapacity data (data year 2013) (http://data.footprintnetwork.org).

- Function: the European share is equal to European biocapacity (i.e. the European population multiplied by the European average per capita biocapacity) divided by world biocapacity (calculated in the same way as the European population).

Computation method 10: economic throughput

Countries are allowed to continue maintaining their level of current production and consumption activities relative to other countries. The allocation to countries is based on the country share of the world gross domestic product (GDP) in PPP at a specific date. Results are computed for 2011 for two scenarios (with and without a cap on income).

- Allocation key: GDP PPP.
- Unit: constant 2010 US dollars per capita.
- Source: World Bank, World Development Indicators (https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD).
- Scenarios:
  - Scenario 1: no transformation; this scenario generates the upper bound value of the shares (21 %);
  - Scenario 2: logarithm of the per capita GDP PPP; as for computation method 7, the index is a normalised version of the natural log: ln(value) - ln(minimum)/ ln(maximum) - ln(minimum).
- Function: the European share is equal to the European GDP PPP (i.e. the European population multiplied by the European average per capita GDP PPP) divided by the world GDP PPP (calculated the same way as for the European population).

Computation method 11: grandfathering

Countries are allowed to use remaining resources or contribute to reduction efforts in proportion to their current impacts. The allocation to countries is based on their share of the overall global environmental impacts computed from a consumption perspective.

The global limit is allocated to countries based on the country share of the global footprint. A single scenario is considered for the year 2011.

- Allocation key: footprints computed in this report.
- Unit: various units (different for each planetary boundary).
- Source: Exiobase 3.4 (http://www.Exiobase.eu/).
- Function: for each planetary boundary, the European share is equal to the European footprint divided by the world footprint. The share mentioned in the table is the median value of the shares.

Allocation principle E: capability

Computation method 12: income

The application of the capability principle (ability to pay) is based on the idea that wealthy countries should contribute proportionally more to reducing environmental pressures than developing economies. This idea is adapted here to match the concept of a budget rather than a reduction target: countries with higher financial capabilities (income) have less right to use resources (or should be able to use fewer resources because of higher efficiency). The allocation to countries is based on an inverse linear relationship with respect to the average per capita income. Three scenarios have been built for the year 2011. The first one considers saturation points of GDP per capita values set at USD 10 000 and USD 100 000 based on minimum/maximum values from the Madison data set. The second scenario considers saturation points at USD 100 and USD 75 000 based on minimum/maximum values used for the standardisation of the income component in the HDI. The third scenario considers saturation points at USD 7 500 and USD 50 000 based on minimum/maximum values proposed in the Climate Equity Reference Project (CERP) responsibility and capability calculator.

- Allocation key: GDP PPP.
- Unit: constant 2010 US dollars per capita.
- Sources: World Bank, World Development Indicators (https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD); Maddison data set (https://www.rug.nl/ggdc/historicaldevelopment/maddison/

releases/maddison-project-database-2018); CERP responsibility and capability calculator (https://calculator.climateequityreference.org).

- Scenarios:
  - Scenario 1: saturation points of GDP per capita values set at USD 10 000 and USD 100 000 (empirical observation of values in the Maddison Project Database);
  - Scenario 2: saturation points of GDP per capita values set at USD 100 and USD 75 000 (the minimum and maximum values used for the standardisation of the income component of the Human Development Index, year 2011);
  - Scenario 3: saturation points of GDP per capita values set at USD 7 500 and USD 50 000 (the minimum and maximum values proposed in the CERP responsibility and capability calculator.
- Function: as in method 7, the European share is equal to the European population weighted by an inverse function of the GDP per capita (see transformations above) divided by the world population weighted by an inverse function of the GDP per capita (as for the European population).

Computation method 13: Cumulative income

The allocation method is similar to that described for computation method 12 but considers cumulative income over the period 1950-2011. The same three scenarios as in computation method 12 are used, based on the same saturation points.

- Allocation key: cumulative GDP PPP (since 1990).
- Unit: constant 2010 US dollars per capita.
- Source: World Bank, World Development Indicators (https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD).
- Scenarios: similar to those described for computation method 10.
- Function: similar to that of method 12, but based on the GDP per capita since 1990 (i.e. the sum of annual GDP PPP from 1990 to present divided by the sum of corresponding populations) and average populations (1990 to present).

Annex 2 Exiobase 3.4 categories

Nitrogen cycle

Exiobase 3.4 contains the following categories of nitrogen releases: nitrogen oxides (NO_x) from combustion and non-combustion to air, N_2O from combustion to air, NH_3 from combustion to air, nitrogen from agriculture to water, N_2O from agriculture to air, NH_3 from agriculture to air, NO_x from agriculture to air, nitrogen from waste to water, NH_3 from waste to air and NO_x from waste to air.

Phosphorus cycle

Exiobase 3.4 contains the following types of phosphorus releases: phosphorus compounds (Pxx) from agriculture to soil, phosphorus from agriculture to water and phosphorus from waste to water.

Land system change

Exiobase 3.4 contains the following land cover categories: cropland, forest area for forestry and marginal use, other land for grazing, fuel wood and marginal use, permanent pastures, and infrastructure land.

Freshwater use

Exiobase 3.4 contains the following types of blue water consumption: agriculture, livestock, manufacturing, electricity tower and electricity once-through.

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doi:10.2800/537187

TH-AL-20-006-EN-N
doi:10.2800/890673

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